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Achieving Wood Energy Potentials: Evidence in Northeastern Minnesota

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ACHIEVING WOOD ENERGY POTENTIALS: EVIDENCE IN NORTHEASTERN MINNESOTA

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FOREWORD

Few doubt the continued significance of wood energy development in the United States, but its precise role in forest management is still unclear. Existing forest products firms are understandably concerned about how expanding wood energy use will affect their raw material costs. Others, convinced of the short-term silvicultural advantages of harvesting wood for energy, are concerned about long-term effects.

The following papers describe a novel integrated approach to assessing wood energy potential in northeastern Minnesota. They represent a significant cooperative effort funded with Energy Security Act monies through the USDA Forest Service. More than 14 scientists and their staffs applied their skills in economics, silviculture, biometry, engineering, forest policy, and mathematics over a 3-year period. Three similar studies were done in other regions.

In the North Central region, we found that wood energy would have more than just a short-term silvicultural advantage. Besides pointing out the significant positive economic impacts on regional employment and fuel cost savings, our study illustrated the usually obscure economic interactions between various wood energy demand scenarios and the long-term costs of all wood products. If long-term forest productivity is important, more rapid wood energy development is a realistic way to achieve it.

Due at least in part to this effort and previous work by the North Central Forest Experiment Station and our cooperators, we can better understand the consequences of wood energy development.

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WOOD ENERGY POTENTIALS IN NORTHEASTERN MINNESOTA

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Minnesota has one of the highest per capita energy uses in the Nation and has no coal, oil, or natural gas. Yet it has vast, underused forests that could meet a significant portion of its energy requirements. A comprehensive study of the situation in northeastern Minnesota is now complete. This study:

1. examined the short- and long-run impact of increased wood energy use on the supply costs of all forest products;
2. estimated current markets for industrial, commercial, institutional, and residential energy;
3. estimated the potential economic and social impact of increased wood energy use by various sectors;
4. identified alternative public policies to stimulate greater wood fuel harvest from Federal, State, County and private land;
5. identified barriers limiting the use of wood fuels; and
6. facilitated efforts among loggers, forest managers, energy users, equipment suppliers, environmental agencies, and regional development agencies to provide for an efficient and equitable transition to increased wood energy use.

This was an interdisciplinary cooperative effort that included the Economics and Forest Survey Projects, North Central Forest Experiment Station; the College of Forestry, University of Minnesota, St. Paul; the Bureau of Business and Economics, University of Minnesota, Duluth; and a St. Paul Engineering Consultant. Funding for this research came from the Boundary Waters Canoe Area Wilderness Act of 1978 and the Energy Security Act.

BACKGROUND

The study area consisted of about 11.5 million acres in the following seven counties of northeastern Minnesota: Aitkin, Carlton, Cook, Itasca, Koochiching, Lake and St. Louis. About 7.4 million acres or 65 percent of the total is commercial forest land and it differs widely by cover type and owner. Public forest land comprises about two-thirds of the study area; 23 percent is federal, 21 percent is state, 22 percent is county, 10 percent is forest industry, and 24 percent is other private.

Hardwood cover types comprise 60 percent and softwood cover types comprise 40 percent of the total. Aspen and paper birch types cover 60 percent and 17 percent of the hardwood area, respectively, and balsam fir/white spruce types occupy 31 percent and 33 percent of the softwood area, respectively. But even this view is confounded because almost all cover types are heavily mixed with hardwood and softwood species. The major concern, as well as current opportunity, is that more than half of the aspen, paper birch, and balsam fir/white spruce types exceeds 40 years of age.

Previous efforts to characterize industrial opportunities for this wood have often emphasized ratios of growth to removals. One recent attempt using this approach found that total annual net growth of all species in the area was about 115 million cubic feet per year compared to estimated annual removals of about 77 million cubic feet. This leaves an annual surplus of about 38 million cubic feet. Presumably, increased harvests would reduce this current surplus as well as future opportunities.

However, mortality in this area was roughly 56 million cubic feet, due in large part to the rapidly maturing or already over-mature forests. Gross growth was 171 million cubic feet (49 percent) greater than net growth. If these trees would have been harvested before they died, the surplus would have been about three times greater or 94 million cubic feet. The point is, under current age class conditions, expanded, not reduced, harvests are needed. Growth to removals ratios are relevant only for a managed or regulated forest with an even age class distribution. Clearly, northeastern Minnesota's forests do not meet these criteria.

Biological opportunities are not the same as economic supply. Simply having a large inventory or the prospect of an even larger one in the future doesn't mean that we should or even could use it. Stand location and access to market, site index, existing stocking, species mixtures, harvest costs, and government regulations all interact to determine economic harvest levels. So, too, a "surplus" cannot be harvested independently of what is already used. Many of the economies of recovering currently unused wood will take place only if we can harvest it along with traditional saw logs or pulpwood. This study focused on timber supply in this broader economic perspective.

Throughout this report, we avoid the term "residue" and refer instead to "wood energy" for two reasons. First, "residue" often carries a negative connotation. Second, the term often only includes branches and tops, bark, cull logs, etc. "Wood energy" also includes all those trees and stands for which no current market exists. Some of these trees may even meet the highest quality standards. Although we do not wish to appear as wood energy advocates, our analysis suggests that any other large utilization opportunity for much of this poor quality material currently is highly unlikely. In the longer run, other more valuable product opportunities may develop. At that time, any use that can return the largest social and economic impact is to be preferred.

MAJOR FINDINGS

We conclude *first*, that northeastern Minnesota's forest resource could supply significantly more wood to an energy market without greatly increasing the cost of other forest products.

Second, harvesting more stands in the next 20 years would enhance future forest productivity; older, slower growing, under-stocked stands would be replaced by younger, faster growing, fully stocked ones.

Third, using more of this wood for local or regional energy needs would reduce regional energy costs, increase total regional output of all goods and services, and increase regional employment. These are critical concerns in northeastern Minnesota.

Fourth, many existing barriers to increasing the use of wood for energy can be removed at low cost by modifying current attitudes and policies that govern forest management. Wood energy is a valid use that is not inferior to sawtimber and pulpwood. Policies can be developed to allow wood energy or any other potential use to compete on its own merits.

MAJOR TASKS

Simulating Future Wood Supply

The pulp and paper industry currently is the largest wood user in northeastern Minnesota, but the waferboard industry recently has expanded significantly. Both use primarily aspen, a species that is currently abundant. Projected increases in demand for aspen raise concern about its future supply. Several studies addressing this type's unbalanced, economically and biologically over-mature condition, suggest that significant shortages will occur in 20 to 50 years if current harvest trends continue. As we shall show, developing wood energy can improve long-term wood supply in general and aspen supply specifically. In other words, it can reduce future wood costs.

Current forest conditions result from past actions. The region's forests, first logged in the early 1900's, regenerated naturally to mostly even-aged mixed hardwood and conifer stands, rather than to the original, mostly pure conifer types. These species mixtures dramatically affect stand values; prices for standing timber can differ by a factor of 10 due often to the presence of unwanted species. If significant portions of a stand are unsalable, a harvest is not usually economical. Unwanted species also hinder regeneration as well as occupy sites that could produce more valuable species.

How would a large wood energy market affect existing timber markets? Two potential complementary impacts are possible. In the short run, an energy market using unwanted timber could make previously uneconomic mixed stands profitable to harvest. In the long run, removing these previously unwanted or uneconomic stands could allow rapidly growing desirable stands to be established for expected larger future needs.

But other factors must be considered for their competitive impact. For example, the locations of wood energy markets often differ from those of ordinary timber markets. Because transport costs are often more than half delivered costs, a stand's location might result in all its' wood being sent to an energy market rather than being shipped to other markets. Similarly, small volumes of more valuable trees may be chipped for energy, simply because sorting wouldn't pay even if its transport would. Of course, these are serious concerns for existing forest industry.

In the past, foresters assumed that demand would increase so rapidly that they would never be able to

produce more than people wanted. Therefore, all stands, regardless of productivity or location, would be needed in a not-too-distant future. In order to meet this ever-increasing demand projection, harvest scheduling attempted to take the unregulated forest (with its unbalanced age distribution and widely differing annual outputs) and move it toward a more uniform and generally, maximum sustainable annual harvest level—so-called "even flow".

However, although most forests are unregulated, regulating them is now perceived to be less important. This is true partly because wood demand has grown only modestly and will probably continue to do so. If we are growing more wood than we can use, all land may not deserve continued investment. And if this is true, management opportunities must be ranked.

In this study we applied a new, more realistic harvesting scheduling model to all land in northeastern Minnesota to estimate the marginal costs of major product groups at various long-term saw log, pulp, and wood energy production levels. We estimated several future "desired" harvest schedules, identified the management alternatives and costs for each cover type, and chose the set of management alternatives that minimized production costs. We then examined marginal costs for each desired harvest schedule. These marginal costs help estimate the total cost incurred to achieve these outputs. In other words, they estimate what people would have to pay in order for the assumed timber investments to be profitable. Of special importance, we examined how the marginal costs of traditional forest products and wood energy interact.

This approach, recently developed by Howard Hoganson and Dietmar Rose, refines previous work on harvest scheduling and takes advantage of the special character of harvest scheduling problems. Briefly, the method is a simulation based on an economic interpretation of the key "dual" variables of a linear programming formulation of the harvest scheduling problem. These key dual variables or marginal costs are interpreted as the "shadow prices" of producing each product in each period.

Timber management scheduling problems rapidly increase in size as more stand information is included. Because a linear programming (LP) solution to these problems requires an exact optimum solution and because there is no way to know before hand when you are "close" to the solution, practical limits on computer time have often restricted the number of stand types to less than 400. The new process accepts near-feasible solutions. Not only is costly computer time saved by not looking for absurdly precise solutions, but also dynamic programming allows larger, more realistic problems to be considered. More than 6,000 stand types were considered in this study.

We used this new model to estimate the costs of meeting several different future wood output scenarios. We looked at future consumption levels for aspen roundwood and softwood roundwood ranging from their current levels of 5.5 and 4.0 million cunits per decade to 9.0 and 8.0 million cunits per decade, respectively. We also examined wood energy output levels from 1 to 30 million dry tons per decade.

Can northeastern Minnesota's forest resource meet these various demands? The question cannot be answered by a simple yes or no but instead can be answered in terms of cost. As Hoganson's paper shows, we have the wood now but unless we start using more of it soon, meeting future needs will be increasingly costly.

Under all future demand scenarios, aspen costs will rise in the next 20 to 30 years. This increase will occur regardless of future harvest level. The crucial point to make, however, is the effect of expanded harvest levels now on aspen costs after this 20-year period. Without expanding harvests now and in the future, costs must rise. That is, cutting more now would reduce future wood costs.

Simulating Fossil and Wood Energy Demand

Bradley and Gephart used a regional input/output model of the same seven-county area to measure the nature of current energy use. The input/output model for the study area, base line 1977, identified 215 sectors and their purchases of coal, petroleum, and natural gas. However, most of the fuel was consumed in only 31 of these sectors, so the remaining sectors were ignored. Using a micro-computer spread sheet, wood requirements and cost savings for several levels of fossil to wood fuel conversions were then estimated. These conversions were then used to create a new wood energy sector for Richard Lichty's analysis of regional economic impact, reported below.

Total fossil fuel use was about $280 million in 1977 (11 percent coal, 61 percent petroleum, and 28 percent natural gas). This does not include transportation fuel costs. The largest fuel users were iron mining, 16 percent; forest industries, 10 percent; petroleum refining, 9 percent; electric utility, 13 percent; gas utility, 8 percent; and households, 19 percent. We felt that the most likely conversion opportunity was judged to be the iron mining, forest industry, and electric utility's use of coal, which accounted for 87 percent of total coal use and 10 percent of all fossil fuel use. It was assumed that about 1/3 of the coal could be replaced by about 1.6 million green tons of wood per year.

The next most likely conversion opportunity was that several sectors' could replace fuel oil with wood for heating and processing. Major sectors assumed to convert would be forest industries, retail trade, health services, government, and households. These sectors used about 50 percent of total fuel oil and 32 percent of all fossil fuel. It was assumed that about 24 percent of fuel oil could be converted to about 1.965 million green tons of wood per year.

A third conversion opportunity would be natural gas also used for heating and processing. Major natural gas converting sectors would be electric utilities, wholesale and retail trade, health services, households, and government. These sectors used about 34 percent of total natural gas and 9 percent of total fossil fuel. It was assumed that about 17 percent of natural gas would be replaced by about 1.162 million green tons of wood per year.

In total then, about 25 percent of all fossil fuels would be replaced by about 4.743 million green tons of wood per year.

How this conversion would be accomplished remains to be seen. Current prices for both fuel oil and natural gas already favor wood (excluding conversion costs). However, coal prices are still lower than those for wood, even though coal conversion would cost the least. Thus, other factors must play a more important role if these conversions are to take place.

Regional Economic Impacts of Wood Energy Development

Using wood for energy probably complements forest industry at the levels assumed above in both the short and long run, but what about the socio-economic impact of such conversions? Using the same input/output model and the above wood energy demand scenarios, Richard Lichty developed new transaction tables including the smaller fossil fuel purchases and larger wood fuel purchases and then inverted them to estimate direct and indirect effects on (1) increased regional employment, (2) increased regional output, (3) fuel cost savings, and (4) induced impacts.

1. *Increased employment.* Under either scenario about 2,000 new jobs would be created, a 1.5 percent increase. About 400 of these would occur directly in the Wood Energy sector. These job increases are not as large as expected but seem reasonable considering the large under-employment in forest harvesting.

2. *Increased output.* Regional output would increase about $100 million in 1977 prices, a 2.0 percent increase. About $50 million of this increase would occur directly in the wood energy area. Here again the 2.0 percent gain in total output compared to only a 1.5 percent gain in total employment is additional evidence of the under-employment characteristic of much of this area's logging and wood transport industries.

3. *Fuel cost savings.* Fuel cost savings would be about $15 million in 1977 prices, about 5 percent of total fuel costs. However assuming 1980 price differentials, this would be about $55 million or 10 percent of total fuel costs.

4. *Induced impacts.* Although the input/output model used could not show it, fuel cost savings would induce added regional growth in output and employment because these dollars would be available to be spent for other things.

Barriers to Wood Energy Development

An important barrier to conversion arises out of traditional concerns about wood supply. Wood consumers must depend on resource professionals for answers. However, the messages conveyed by them have been contradictory. Nationwide, some forestry agencies continue to raise the traditional spectre of rising wood prices and large shortages for as long as they care to project. Others have identified dramatic surpluses in many regions of the U.S.

On the whole, most land management agencies, have taken the traditional view and have not dealt with the contradictions inherent in more specific resource analyses. Resolving the technical questions of shortage vs. surplus in realistic regional analyses is an important step in addressing what we feel is a nationwide problem of unnecessarily low wood utilization.

Another key obstacle to addressing wood energy development in particular and poor wood utilization in general have been many agencies' negative attitudes towards wood energy or any other nontraditional, presumably inferior use. Resource professionals must be more neutral to wood use opportunities. Any use that can compete in a free market should be welcomed. Of course, we cannot expect existing wood using firms to embrace potential threats to their wood supplies of long standing. However, it should be possible to avoid the "we vs. they" issues and concentrate on real and solvable aspects of this problem.

Ellefson *et al.* outlined an extensive list of programs and policies that could encourage wood energy specifically and wood utilization generally. These policies were also rated on the basis of several criteria but were not ranked. It seems that the technical and financial obstacles are being addressed and that government at any level is poorly equipped to deal with them anyway.

However, regulatory and administrative perspectives, often based on traditional but arbitrary rationales, are fertile grounds for change.

Policy Recommendations

Wood energy development will require a host of individual actions by entrepreneurs as well as concerted action by agencies. Considering the preponderence of public land in northeast Minnesota and our previous discussion of barriers, it seems logical to expect most of the critical initiatives to come from the County, State, and Federal land managers in the region. The major question is wood supply! All other issues and policies depend on how wood energy is viewed to fit into the total wood supply picture. If supply is really tight and real prices for saw logs and pulpwood exceed wood energy, or are expected to do so soon, then timber sale and pricing policies should probably parallel current practices.

However, we feel that a long-term view of the forest situation in northeast Minnesota shows (1) a large resource surplus, as evidenced by both real price declines and expanding inventory; (2) a large economically overmature age class imbalance with a corresponding high mortality; (3) the imminent "loss" of money already spent to grow and protect this large surplus during the last 60 years unless a great deal more is used soon; and (4) even higher future wood costs due to the lost opportunity to use now and thereby set the stage for enhanced forest output later.

Given a large, current, short-lived surplus, and the chance to enhance future output at lower costs, all those attitudes and resulting policies that arbitrarily obstruct wood utilization must be changed. For public and private forest resources to play a larger role in economic development, forest policies must reflect the economic realities. Surely, current ones do not. Primary forest production and primary forest industry in northeastern Minnesota are not competitive in an economic sense. There are at most, a dozen or so wood buyers and no more than half as many significant wood growers. This situation is more characteristic of the U.S. energy industry than U.S. agriculture, yet agricultural pricing and marketing policy models are used.

Instead of trying to sell a few cords or board feet of wood at a time, larger, long-term sale and pricing agreements could be considered. Exclusive and long-term coal, oil, and gas leases on public and private land are negotiated based on the economic reality that little investment will occur without them. Similar marketing policies are needed for wood, too. Such radical changes would require overcoming some significant political obstacles, and other less dramatic ways may accomplish the same thing. But existing forest industries must be given opportunities to help formulate these policies. If northeastern Minnesota's wood-using opportunities have a time limit, existing firms could be given right-of-first-refusal on the use of much of the surplus. Surely no one would lightly propose losing two jobs to gain one, even if the change resulted in increased value added. However, if those options are refused, it would seem to be the public land manager's responsibility to seek firms who will.

SUMMARY

This study of the effects of wood energy development shows what could exist, not necessarily what should exist, in northeastern Minnesota. Results indicated that the impact of increased wood energy use would be largely complementary to traditional forest industry. The mechanism is simple: in the short run, a wood energy market would reduce the variable costs of all wood products by enabling many previously inoperable stands to be harvested profitably. In the long run, wood energy markets would lower fixed and variable costs of all wood products because slow-growing, overmature, poorly stocked areas would be replaced by well-stocked, rapidly growing stands.

Northeastern Minnesota is currently a hotbed of changing forest resource management perspectives. Each of the three major public agencies are seeking opportunities to address their budget limitations, improve wood utilization, respond to regional economic growth initiatives, and provide greater socio-economic rationales for their programs. Wood energy development is attracting a lot of interest. Our findings, especially on the critical interactions between current wood energy development and future supplies of traditional sawtimber and pulpwood, should provide viable alternatives for land managers.

PREDICTING MULTIPRODUCT TIMBER YIELD FOR LONG-TERM SUPPLY ANALYSES[1]

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Basic forest management concepts such as sustained yield, allowable cut, and even flow are all based on long-range supply analysis. Each National Forest in the United States is required by law (National Forest Management Act of 1976) to examine the long-term timber supply in its overall forest management planning process. Other Federal land management agencies also employ long-range supply analyses as an integral part of forest management, as do many State, county, and private landowners.

The slow growth of most timber species makes long-range planning especially important. Long-term production can be strongly affected by harvest cycle and harvest technique. The decisionmaking process must include not only the direct costs and benefits from initial harvest, but also the impacts of today's harvest on future timber supplies. This complicates the manager's problem of selecting a harvest quantity and species mix, especially for mixed-species forests that rely heavily on natural regeneration.

[1] *Research supported by the College of Forestry and the Agricultural Experiment Station, University of Minnesota, St. Paul, Minnesota; and the U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota; under Cooperative Research Agreement 23-82-17.*

[2] *Formerly Forest Economist, U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station, Duluth, Minnesota.*

With the advent of the computer and development of timber harvest scheduling models, comprehensive long-range supply analyses (Jameson *et al.* 1982) are now possible. But unfortunately, it has not been easy to assemble, for a large region, precise and accurate yield estimates for numerous potential products by species and stand treatment alternatives for many different stand types. The number of distinct stand types can be very large, because age, density level, site quality, and species mix all influence tree growth and product yield. Attempts to assemble this information have also been frustrated by the fragmented results of growth and yield studies, by prediction models that address only a few species or cover types, and by incompatibility among models in terms of inputs and outputs. Further, existing multispecies models are still far too slow and costly in execution to be utilized as subprograms called by optimization algorithms that must examine many alternatives. This paper addresses these problems by describing a practical procedure for developing multiproduct yield estimates. The yield tables and estimation procedure, which are currently being used as the basis for several long-term analyses, illustrate techniques that can be applied widely in forest management planning.

INFORMATION NEEDED FOR TIMBER SUPPLY ANALYSES

The procedure described here evolved from attempts to develop growth and yield information for northeast-

ern Minnesota to assess the impact of alternative short-run harvest opportunities on the long-run timber supply. Growth and yield data from this region have been published in a variety of forms for a number of species over the last 60 years (see Ek and Brodie (1975) and Schlaegel (1971) for aspen; Buckman (1962) and Lundgren (1981) for red pine; Benzie (1977) for jack pine). Unfortunately, the various growth and yield tables or models described in these and similar reports do not cover all of the pure and mixed-species stand conditions of interest nor do they provide much detail on growth response to varying stand densities.

Consider, for example, stands that fall into the aspen cover type, a major cover type in northeastern Minnesota. Many aspen stands contain significant volumes of other species; in fact, this "other" component can be the major value component of the stand. Two aspen stands might each contain 24 cords of aspen per acre, but one might contain an additional 6 cords per acre of birch while the other contains 6 cords of a softwood species. In terms of northeastern Minnesota prices for timber sold on the stump, aspen is selling for approximately $2 per cord, while birch is selling for less than that. Softwoods, however, could easily return $25 or more per cord depending on species and tree size. Based on these values, timber harvest returns from the first stand would total less than $60 per acre, while those from the second would be approximately $200 per acre—over three times as much. From a financial viewpoint it is clear that these are two different stand types, yet available growth and yield models lump stands like these together, and give little if any detail on species breakdown. Further, with most models, inputs differ and outputs are limited in terms of the number and type of products.

Conducting supply analyses with conventional growth and yield information requires either the collection of additional data or a method of synthesizing existing data. Time and cost constraints dictate a focus on the latter alternative. Desirable characteristics of the needed growth and yield estimation approach are that it be:

1. Capable of projecting yields for any age of possible final harvest.
2. Compatible with harvest scheduling models to the extent that it does not further complicate the scheduling process or unnecessarily increase its cost.
3. Detailed in terms of yields for a wide variety of tree product breakdowns by species.
4. Sensitive in terms of the relationship of growth to stand density, site quality, and species composition.
5. Smooth with respect to growth and yield patterns both in terms of total volume yield and for species breakdowns.
6. Easily and rapidly accessible by computer.

Smooth growth and yield curves are desired because optimization techniques used in the scheduling process cannot always filter out irregularities or random variation. Scheduling models treat all inputs as knowns and thus irregularities in growth and yield curves can significantly affect scheduling results.

Recently, a large number of individual tree-based stand growth projection models have been developed that can provide detailed growth and yield information for a wide variety of stand conditions. These models are generally accurate for short-run projections, but they are not well tested and accepted for projections beyond 20-30 years. Longer projections are very sensitive to the ingrowth and mortality components of the system and projection errors can be magnified over time. Furthermore, test data for longer periods are still limited. Consequently, the utility of these growth projection models for long-run timber supply analysis is questionable.

Another approach is to develop empirical yield tables (Husch *et al.* 1982) based on recent forest inventory plot information. This approach has limitations, however, in that past cultural and harvesting practices may preclude the possibility of these plots adequately representing all stand conditions for each age and site class. In fact, the small sample size for the recent inventory of northeastern Minnesota did not provide enough plots to develop detailed yield tables by age and site class for all of the cover types of interest (Hahn and Essex 1982).

COMBINING YIELD TABLES AND GROWTH MODEL PROJECTIONS

Our methodology overcomes some of the problems of empirical yield tables and growth projection models by combining the two approaches. By using a growth projection model, additional plot data points can be generated for developing more complete empirical yield tables. Using plot growth projections along with the original plot data adds serial correlation to the data, but this correlation also helps smooth the growth and yield curves. Also, the additional data points generated allow more detailed information on yields for some site-quality classes. For example, the existing stands that fall into older age classes tend to be of poorer (less harvestable) site quality or they are residual stands left after some partial harvest. Site quality influences growth and yield, but by using survey plots alone, it is often difficult to recognize site quality differences because data are often lacking for older-age, high site quality classes. This problem is overcome by the addition of observations developed from projections.

Our methodology evolved as three steps. STEMS, the Stand and Tree Evaluation and Modeling System

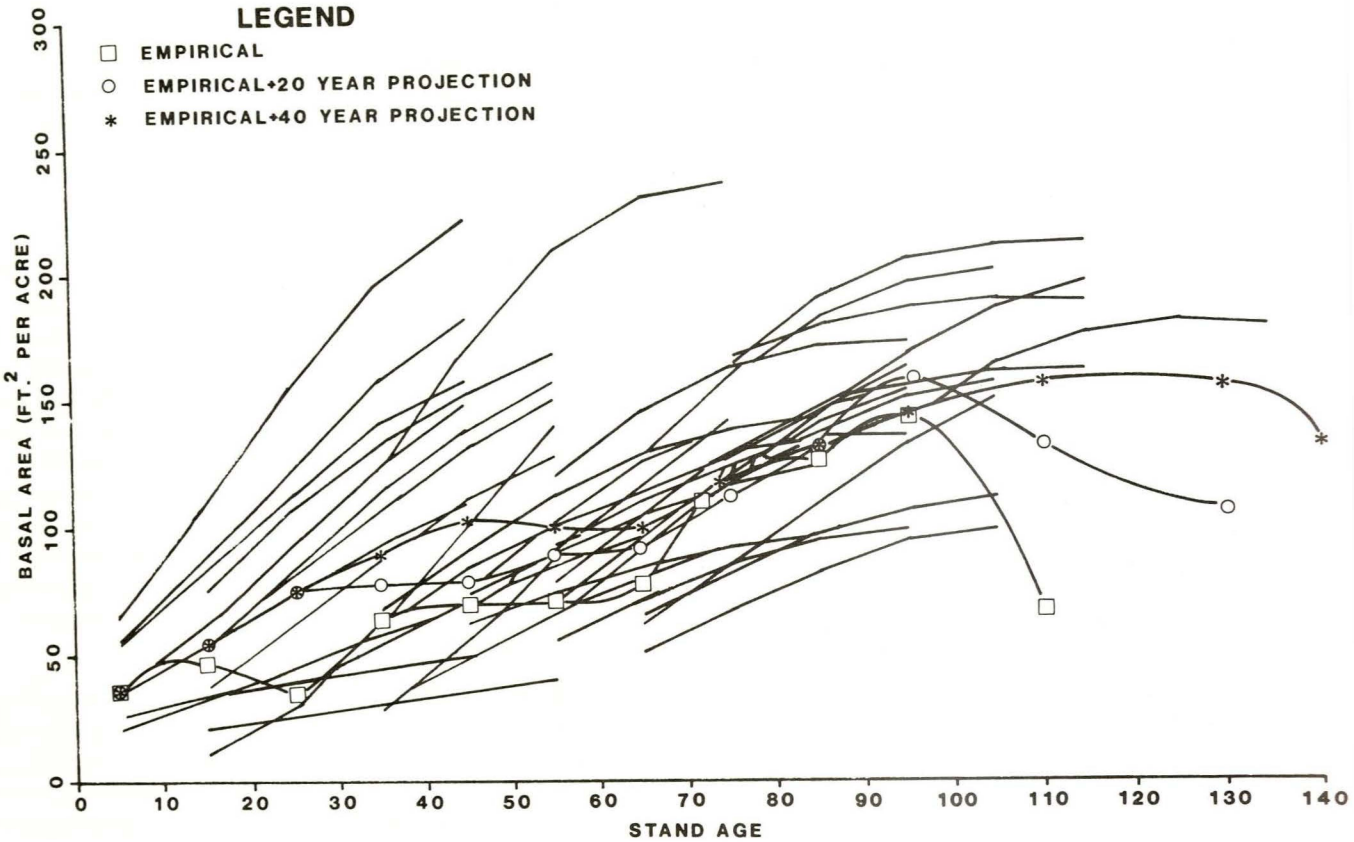

Figure 1.—*Basal area over age for* aspen with 10 percent or more pine (site index 0-65) *type by averaging option: empirical yield data; empirical yield data plus 20-year projections; empirical yield data plus 40-year projections. Fine lines represent projections of a systematic sample of plots. Heavy (smoothed) lines are based on graphics package algorithm and included for illustration only. Based on 79 plots.*

(Belcher 1981) was used for all growth and yield projections, and 4,567 inventory plots established during the 1976-1977 Minnesota inventory[3] (Jakes 1980) served as the basic data source. The STEMS projections were made using the deterministic mortality option in the model (Belcher *et al.* 1982).

The *first* step was to project the plots for 40 years to assess which plots were likely to change cover types. Relatively few of the plots, less than 5 percent, actually changed cover type definition as determined by a basal area-sorting algorithm. In practice, a handy wall-mounted cross tabulation of plot frequency by initial type and type after a 40-year projection was used in guiding these specifications. Based on these projections and the direction of cover type changes, some 43 species group and site class combinations were specified. Hereafter these combinations are called "types." The *second* step was development of type-specific empirical yield tables using only the survey plot (empirical) data. Within each type class, plot yields were averaged by 10-year age class. The *third* step was identical to the second step except the number of data points (plots) was increased significantly by including as data points the 10-year, the 20-year, the 30-year, and the 40-year STEMS projections for each plot. This step produced approximately smooth growth and yield curves in nearly all cases.[4] Curves for basal area are illustrated in figure 1, along with 40-year projections of a systematic sample of the individual survey plots. Note that the incorporation of projections tends to raise and smooth the basal area/age relationship. Plotting projection results suggests that either the projections are overestimating growth or that the older age empirical yields do not represent a real older stand growth series. However, some raising of the average would be expected because the projections generally do not incorporate the effect of catastrophic events such as blowdown, fire, land use changes, epidemics, etc.

[3] *Plots established by the Forest Inventory and Analysis Research Work Unit at the North Central Forest Experiment Station, Forest Service, U.S. Department of Agriculture.*

[4] *This step was also attempted with 30-year rather than 40-year projections, but the latter provided more satisfactory smoothing.*

Unfortunately, the actual magnitude of that effect is indeterminate at this time. It was the authors' judgment, however, that the combination of the projection and empirical yield data produced a more realistic estimate of the actual growth series than either data source by itself.

A *fourth* step for some cover types involved the further smoothing of the basal area versus age class relationship. Several smoothing approaches were examined, including polynomial models relating basal area to age, but the most satisfactory was simply

$$B_t = \frac{1}{4} \cdot [B_{t-1} + 2B_t + B_{t+1}]$$

where B is basal area and t is the age class.

APPLICATION PROCEDURE

The data combination and smoothing process is illustrated in figure 1. The results provided an average basal area for each of the 43 species group/site class types for each of 14 10-year age classes to age 140. Average stand yields for some of the corresponding merchantable products are shown in table 1. The various product outputs were developed by applying different tree volume and biomass equations (Hahn 1984) to the individual tree data for each plot. These yield tables are converted to an average yield per unit of basal area and adjusted to the smoothed basal area when the tables are accessed by the supply analysis model. The result is a set of rapidly accessed "look up" yield tables for each age class. The forest-wide species composition is in large part handled by the original species group/site class stratification. When a stand is harvested, it is replaced by the youngest age class corresponding to the species group it would likely become. In the case of artificial regeneration, the stand could be converted to a different species group.

Growth and yields for nonaverage stand conditions within a type can be developed in several ways. We assumed simple proportionality: the growth and yields of stands with basal areas differing from the smoothed average were considered to be higher and lower than the average according to the proportion their basal area was of the average. For example, a stand with 20 percent more basal area was assumed to have a 20 percent higher yield at that and subsequent ages. We also considered approaches which assume that stands grow towards some normal or full stocking level over time, but with the exception of the red and white pine type, there was insufficient evidence in the data to support these approaches.

VALIDATION AND EFFECTIVENESS OF THE APPROACH

Unlike those in figure 1, the red and white pine projections in figure 2 show definite upward crossing of the empirical yield curve. Such patterns were not evident for other species, perhaps in part due to infrequent thinning of those species and their limited response to thinning. Thus, the simple proportionality assumption noted above seemed to work well. Red and white pine, however, are known to respond to thinning at even advanced ages. Consequently, a variation in procedure for estimating basal area growth for this type would be to express it as a function of stand density or perhaps use the simple stand basal area growth equation developed by Buckman (1962).

As a caution to users, note that the yield table (table 1) is broken down to only four species groups. It is possible to partition these data to a finer level of species and product aggregation; however, the yield-over-age pattern becomes increasingly irregular when that is done. Thus, the approach may still have limitations for study of individual species in mixed species stands.

Users may also question the large average diameter for 11- 20-year-old stand given in table 1. However, it is important to recognize that this value represents a combination of young trees and residual stems following harvesting. It is the average of what was found in the inventory for this age, site, and type. It is thus a good estimate of what we might expect on the average, given recent management.

The above procedure is not mathematically or statistically elegant. However, it is effective in developing more realistic growth and yield information in a rapidly accessible form compatible with harvest scheduling models. It does provide some sensitivity to differing stand densities and varying species composition. It also provides simplicity in use and interpretation of the tables, both within the computer and for the analyst. As growth observations for long periods become more readily available, it will be appropriate to more rigorously test the validity of assumptions here and perhaps rely more heavily on projection models. Growth of volume by product and assumptions about species composition stability by strata are first priorities for testing.

At present there are few geographically extensive growth observations covering a long time period—and none in the study region. Despite this lack of observed

Table 1.--Average yield per acre and stand characteristics by selected age classes for Aspen with 10 percent or more pine (site index 0-65) type [1/]

Product class[2/]		Unit of measure	Age class (years) 11-20	31-40	51-60	71-80	91-100	121-140
Pine & spruce	GS	cubic feet	174.5	456.6	580.4	724.1	1,105.2	1,612.0
Pine & spruce	SL	cubic feet	116.1	348.0	412.0	569.2	907.5	1,353.5
Pine & spruce	US	cubic feet	31.5	70.4	73.9	106.5	164.5	206.4
Pine & spruce	AL	green tons	6.7	17.2	21.5	24.7	37.5	53.7
Softwoods	GS	cubic feet	49.4	127.5	161.3	219.9	292.8	121.5
Softwoods	SL	cubic feet	20.1	68.7	72.6	117.1	179.1	64.8
Softwoods	US	cubic feet	8.4	24.9	25.4	42.5	51.5	28.7
Softwoods	AL	green tons	2.7	6.2	7.2	9.9	12.6	3.9
Aspen	GS	cubic feet	251.2	514.6	573.4	772.0	954.4	678.3
Aspen	SL	cubic feet	110.6	254.2	335.5	563.9	776.5	583.7
Aspen	US	cubic feet	28.4	67.7	96.0	138.3	153.9	94.6
Aspen	AL	green tons	18.3	28.7	30.6	39.3	47.8	36.0
Hardwoods	GS	cubic feet	126.0	261.5	242.6	315.1	395.4	662.8
Hardwoods	SL	cubic feet	38.3	120.9	101.8	176.2	215.2	309.8
Hardwoods	US	cubic feet	13.6	43.0	31.1	53.9	58.8	99.2
Hardwoods	AL	green tons	9.0	15.8	17.1	20.9	24.4	40.8
Average diameter								
Softwoods		inches	9.4	12.5	13.2	13.7	15.8	15.2
Hardwoods		inches	6.4	8.4	8.3	10.0	12.2	13.0
All species		inches	6.8	9.0	9.1	10.5	12.9	14.2
Average basal area		square feet	55	90	100	119	144	156
Number of plots (actual)			11	9	12	7	1	0

1/ Raw, unsmoothed values from combination of actual plot yields with 40-year plot projection results.

2/ Definitions:
Pine & spruce = white and red pine and white spruce
Softwoods = other softwoods
Aspen = Bigtooth and quaking aspen
Hardwoods = other hardwoods
GS = growing stock trees $\geq$ 4.95 inches d.b.h. (see Jakes (1980) for tree class descriptions)
SL = Saw log portion of trees $\geq$ 8.95 inches d.b.h.
US = Upper stem portion of trees $\geq$ 8.95 inches d.b.h.
AL = All live trees $\geq$ 0.95 inches d.b.h.

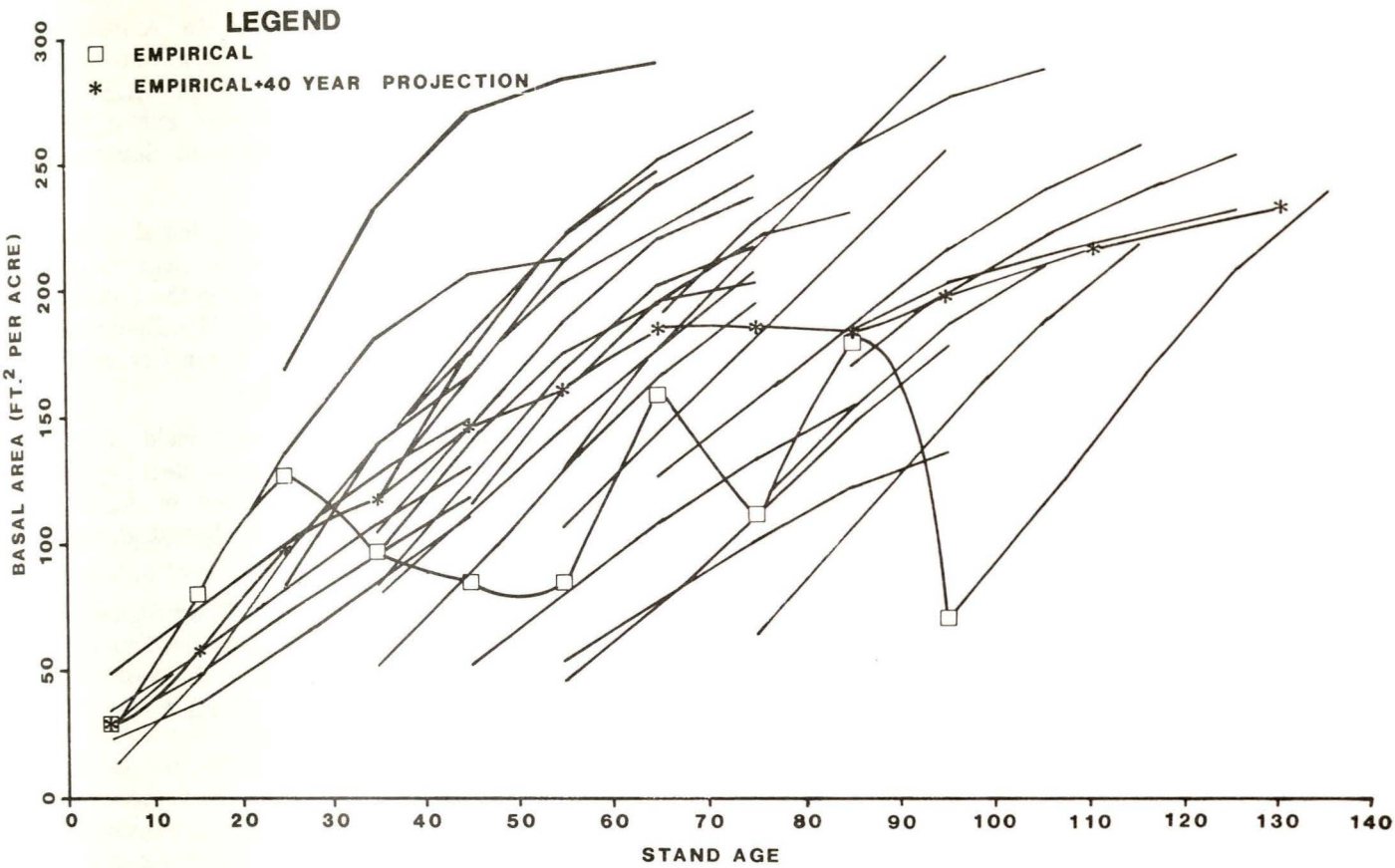

Figure 2.—*Basal area over age for* white and red pine (site index 61 +) *type by averaging option: empirical yield data; empirical yield data plus 40-year projections. Fine lines represent projections of a systematic sample of plots. Heavy (smoothed) lines are based on graphics package algorithm and included for illustration only. Based on 37 plots.*

growth data, there is validation information in the data. The growth model (STEMS) has been widely tested and is known to be adequate for short periods (Leary and Hahn 1979, Smith 1982). Also, graphs like figure 2 were evident for all but the red and white pine cover types. As in figure 1, the approximately parallel pattern of STEMS predictions around the empirical yield data curve suggests validity for both as descriptions of growth-over-age patterns. Until surveys are expanded or growth models are refined, this methodology does suggest a way to meet harvest scheduling analysis needs. It is offered here not as the ultimate approach, but as an operational strategy that we hope will be refined later.

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IMPACTS OF WOOD ENERGY USE ON TIMBER SUPPLY IN NORTHEASTERN MINNESOTA

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Forests in northeastern Minnesota have the biological potential to supply significantly more wood than currently is being consumed by existing forest industry. One often-suggested proposal is to utilize this timber supply surplus for energy production. This use might complement forest industry in both the short and long run. A short-run benefit would be the opportunity to recover the desirable species contained in the many mixed-species stands that wouldn't be harvested without an energy market. Although the proportion of desirable species in these stands is relatively low, the total volume of desirable species is large because these stands cover so many acres. A long-run benefit would be the increased future forest productivity due to harvesting now. Many older, slower growing stands need to be harvested now to achieve their productive potentials, and so-called "off-site" stands can be converted to more desirable species.

THE PROBLEM

A major concern about wood energy use is the negative impact it might have on existing forest industries. Undoubtedly, more stands might become marketable with a larger wood energy market, but how much wood suitable for existing industry would actually be burned? Obviously some of this material would be utilized simply because it is closer to a wood energy market or because it is too expensive to sort out during harvesting operations.

Northeastern Minnesota has an enormous biological supply of woody biomass (Raile and Jakes 1981), but the biological supply is quite different from the economic supply for specific forest industries. By definition, economic supply is a schedule that shows the quantity *producers are willing to sell at each price during a specified time period. Economic supply is a difficult concept for specific forest products, such as wood energy, for at least four reasons. First, many forest resources can be supplied to any one of several product markets, thus making the economic supplies of many forest products interrelated. Second, the supplies of not-so-similar forest products can also be interrelated because they occur as joint products in individual stands. Third, because considerable time is required to grow trees and because they can be harvested at different ages, the current economic supply and future economic supplies are interrelated; future economic supplies depend on actual harvest levels during prior periods. Fourth, the wood produced within a region is supplied by many different landowners, each with his own management objectives and strategies.*

Predicting the economic supply of wood energy or any other specific forest product is thus a difficult, if not impossible, task. Yet, it is important to better understand the value of increased wood energy use and how such increased use might affect timber supplies for other forest products.

OBJECTIVES

The objective of this study was to examine the economic timber supply situation in northeastern Minnesota to gain a better understanding of the opportunities for increased wood energy production. The objective was not to predict future wood energy consumption, but rather to try to examine the future opportunities that might be possible over a range of plausible future conditions. Specific objectives were to:

1. Determine least cost management schedules for producing plausible future timber product outputs.
2. For each least cost management schedule, identify the marginal production costs for each product and

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how they change as the wood energy production level changes.

3. For each least cost management schedule, estimate the net present worth (NPW) of the schedule under several wood energy price assumptions and identify how NPW would change as the wood energy production level changes.

4. Identify how wood energy production can best be incorporated into the joint timber production process.

METHODS

Energy models are typically not good forecasting devices. As discussed by Samouilidis (1980) "There is ample evidence, both theoretical and empirical to support this claim." The primary use of energy models is in gaining a better understanding of how systems operate. The system in this case is the timber production system in northeastern Minnesota. A relatively small region is considered because biomass energy must be considered on the basis of a specific market area (Silversides 1982). High transport costs and varying local wood markets force this perspective.

Several previous studies have looked at wood energy supply potential for specific areas of the Lake States. Raile and Jakes (1981) reported total green ton biomass estimates for northern Minnesota from the most recent forest survey information. Aube (1980) evaluated the economic feasibility of supplying a wood-fueled power plant in northern Minnesota. Bradley *et al.* (1980) examined the wood energy supply potential for northern Wisconsin and Michigan. But none of these studies attempted to measure the impact of increased wood energy use on the supply costs for other wood users. Methods for measuring such impacts are not well defined. Greber and Wisdom (1985) examined the short-term impact of wood energy use on existing pulpwood and saw log markets in eastern Virginia using a simulation model. They were able to identify substantial short-run interactions between markets, both complementary and competitive. Long-term interactions were not considered.

Linear programming (LP), which has been the major technique used in energy modelling (Samouilidis 1980), is also a primary tool used in forest-wide timber management scheduling. Significant information about timber supply costs can be gained from the dual variables associated with the optimal solution to an LP timber management scheduling model. Using a cost-minimization approach, the dual variable associated with each forest output level constraint represents the marginal cost of production for that output. By comparing the dual variables (marginal costs) for runs with different output levels over time, much can be learned about the impacts of wood energy output levels on the supply costs of other forest products. Model size is the greatest limiting factor in performing analyses of this type (Johnson and Scheurman 1977, Jameson *et al.* 1982); current LP timber management scheduling models were considered inadequate, because they could not recognize enough of the stand detail that is so important for wood energy considerations.

Instead, a scheduling method developed by Hoganson and Rose (1984) was used for this study. Their method was applied to a harvest scheduling linear program to minimize the cost of producing specified forest output levels. This method uses basic concepts of dynamic programming and timber production economics and is based on the dual interpretation of the problem. The dual variables associated with the forest output level constraints are the key dual variables in the solution process. If their values can be determined, then the problem can be decomposed and solved in parts. And because of this decomposition and solution in parts, significantly more stand detail can be included in this model.

The following steps comprise the method: (1) the key dual variables are estimated *a priori*, (2) these estimates are used to solve for the remaining variables, (3) the harvest schedule implied by these estimates is compared to the desired harvest schedule to determine the accuracy of the *a priori* estimates, and (4) if the errors in the estimates are significant, the implied schedule results are used to re-estimate the key dual variables and the process is repeated. If the implied schedule is close to the desired schedule, the key dual variable estimates must be close enough. The economic interpretation of the key dual variables and some simple concepts of timber production economics are important aspects of the re-estimation process used in step (4).

THE DATA

Data requirements were enormous. The study considered all forest lands in the seven northeastern Minnesota counties of Aitkin, Carlton, Cook, Itasca, Koochiching, Lake, and St. Louis, for a total of approximately 7.3 million acres. Ten 10-year planning periods were considered, with the first beginning in 1976, the year of the most recent forest survey.

The stand classification scheme, which allowed for over 6,000 initial stand types to be recognized in the model, was based on site type, current species mix, stand age, stocking level, distance to the nearest wood energy market, and distance to the nearest existing roundwood market. Twelve site types were recognized. Site types were defined by both the site productivity (site index) and the species mix that would result naturally after a clearcut. Each site type was divided into

classes based on species mix of the initial stand, with as many as 10 classes recognized per site type. Numerous species mixes were possible, thus a fair amount of aggregation was needed. During the aggregation process consideration was given to both the silvicultural characteristics and economic values of the species involved. Site by species-mix types were subdivided into 10-year age classes and two relative stocking levels (high or low). The final levels of classification were two distance-to-market identifiers, one representing the distance to a wood energy market and the other representing the distance to an existing roundwood market. Cities with a population of at least 2,000 were considered as energy markets. For both distance identifiers, the classes were three relative measures: close, medium, and far.

Twelve forest products were recognized by considering all combinations of four species groups—valuable softwoods, other softwoods, aspen, and other hardwoods—and three product size classes—saw logs, pulpwood, and other woody biomass. Output (production) levels for three forest product groups—softwoods, aspen, and wood energy—were used to define scenarios. All of the 12 forest product types were considered as possible wood energy sources. For example, other softwood pulpwood could be used to help meet either the softwood output level or the wood energy output level. Within each forest product type group, value differences were recognized among specific product types. For example, valuable softwood saw logs were assumed to be worth $40 more per thousand board feet than other softwood saw logs. Value differences were based on differences reflected in recent Minnesota forest product price reports.

U.S. Forest Service permanent survey plots were used as the basis for describing the initial conditions of the forest (Jakes 1980). Plot locations were linked with a classified grid describing the relative location indices. Information on the location and demand of existing markets was obtained from a number of sources, including Blyth *et al.* (1979), Blyth and Smith (1983), and Milton and Krantz (1982).

Growth and yield data requirements were enormous. Considerable growth and yield information is available, but very little specific attention has been given to the differences in species mixtures that occur within a given major species type. For example, all stands with aspen as the major species are usually lumped together, with little attention given to how aspen stands vary in terms of other species present. Information is also lacking for making accurate long-term growth projections.

Growth and yield information was developed using a technique developed by Ek *et al.* (1984) that combined recent survey data with projections from the STEMS growth projection model (Belcher *et al.* 1982) to develop empirical yield tables (Husch *et al.* 1972). Computer software was developed to automate the process of using the empirical yield tables and harvest cost information to formulate possible management alternatives for individual stand types. Prescriptions included the timing and amount of all costs and yields. The prescriptions were primarily clearcuts that varied significantly as to the time of harvest and the type of harvest system applied. Traditional roundwood-only systems, full-tree chipping systems, and chip-and-sort systems were all considered. Harvest cost estimates were based on harvest cost and production data described by Bowyer and Hazenstab (1984). Thinning alternatives were considered for red pine sites.

Dynamic programming was utilized to link first-rotation management alternatives with regeneration alternatives. The latter included natural as well as artificial options, such as site conversion to valuable softwood species. A "no harvest" option assumed that the stand followed natural succession toward either a climax hardwood or softwood type. The natural regeneration options were based on the same growth and yield information developed for the initial rotations. Alternatives for red pine plantations developed by Lundgren (1981) and modified by Lothner and Bradley (1984) represented the valuable softwood conversion option.

Wood consumption levels are difficult if not impossible to predict for periods far into the future. Instead of attempting to forecast specific consumption levels for each product group, six plausible scenarios in future output levels were considered (table 1). Each scenario is defined by a set of desired output levels over time for the aspen and softwood product groups, and a general assumption about the future role of wood energy: wood energy use will continue indefinitely at a constant level or remain constant for the next 30 years and then drop to 400,000 dry tons per year, a level close to the existing consumption level. Both a constant output trend and a rising output trend were considered for aspen and softwoods. Under the rising softwood trend, the increase is linear such that the output in period 9 is double the output in period 1. For all scenarios, the aspen output level increases between period 1 and period 2 to reflect the recent growth in the waferboard industry. For the rising aspen trend, output does not increase again until period 5, because preliminary results indicate that aspen is currently close to its maximum sustainable level. The specific desirable output levels considered for the aspen and softwood product groups are shown in table 2 in the Appendix.

Table 1.--Description of the six scenarios

Scenario	Description
1	Aspen and softwood outputs constant over time and wood energy use continuing indefinitely.
2	Aspen output constant over time, softwood output increasing over time, and wood energy use continuing indefinitely.
3	Aspen and softwood outputs constant over time and wood energy use primarily a 30-year opportunity.
4	Aspen output constant over time, softwood output increasing over time, and wood energy use primarily a 30-year opportunity.
5	Aspen output increasing after 40 years, softwood output constant over time, and wood energy use primarily a 30-year opportunity.
6	Aspen output increasing after 40 years, softwood output increasing over time, and wood energy use primarily a 30-year opportunity.

RESULTS

Several runs of the timber management scheduling model were performed for each of the six scenarios, for a total of 34 runs. The final marginal cost estimates for each run are shown in the Appendix. In the pages that follow, the major relationships identified will be described, the schedules developed for one scenario will be summarized briefly, and implications of the scheduling results for selecting a wood energy output level will be considered.

Supply Cost Interactions

Graphs of marginal production costs plotted against time are good indicators of the general timber supply situation. For a perfectly regulated, one-product forest in which output levels remain constant over time, the plot of marginal production cost against time (using corresponding period dollars) would be horizontal. If the age distribution of the forest were imbalanced then a cyclical line would be expected. Market location, multiple product interactions, and changing output levels are just some of the factors that can change the marginal production costs of specific timber products over time. In this section the focus will be on the impact of alternative wood energy output levels on the marginal production costs of three timber product groups recognized in the model.

Aspen marginal costs plotted against time for scenario 1 indicate both a complementary (fig. 1) and competitive (fig. 2) relationship between wood energy use and aspen production. Aspen marginal production costs decreased as wood energy production level increased from 1 to 10 million dry tons per decade, and then increased as the wood energy production level increased from 10 to 30 million dry tons per decade. Between the 6 and 12 million levels, changes were insignificant, but increasing the wood energy output from 20 to 30 million dry tons per decade greatly increased aspen marginal costs.

All of the aspen marginal cost curves for scenario 1 peak in year 2010 (figs. 1 and 2). These peaks reflect the general aspen "shortage" that has been projected for the area because of imbalances in aspen age distribution. Forty years is the minimum rotation age assumed for aspen in the model; aspen marginal costs drop by 2020 because benefits from regeneration work undertaken in the first period are realized.

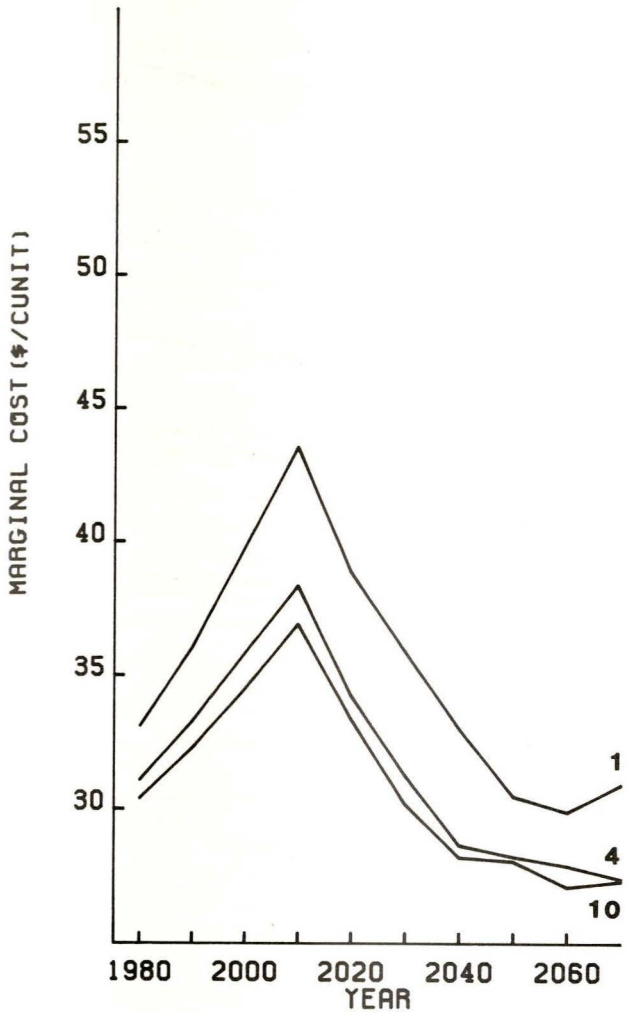

Figure 1.—*Aspen marginal cost estimates for low wood energy levels for scenario 1: aspen output constant, softwood output constant, and wood energy use continuing indefinitely. (Curve labels indicate the wood energy output level in millions of dry tons per decade.)*

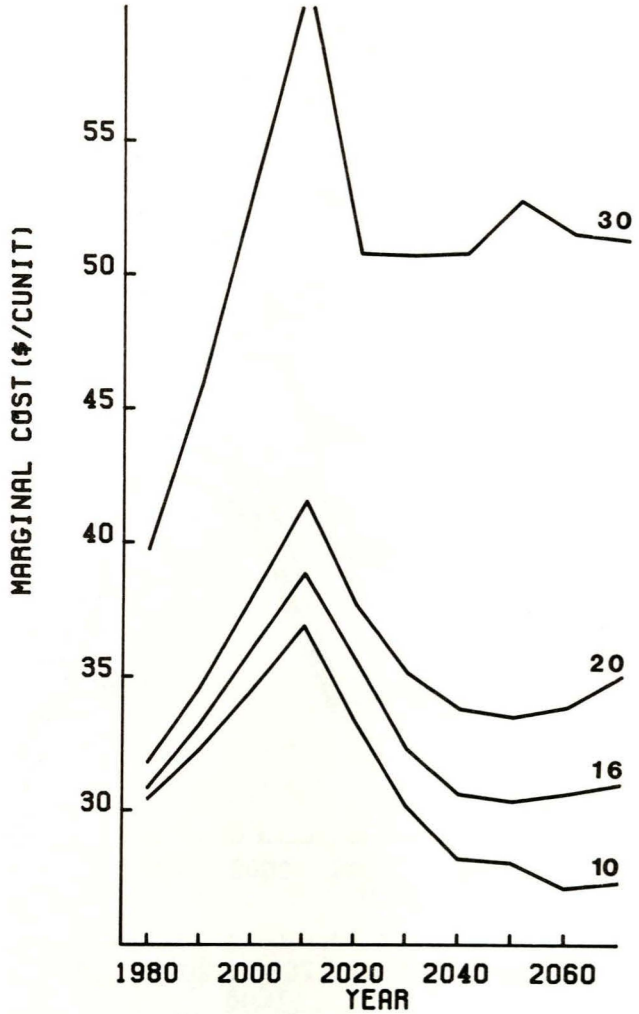

Figure 2.—*Aspen marginal cost estimates for high wood energy levels for scenario 1: aspen output constant, softwood output constant, and wood energy use continuing indefinitely. (Curve labels indicate the wood energy output level in millions of dry tons per decade.)*

Softwood marginal cost estimates are not sensitive to the wood energy output levels examined for scenario 1 (fig. 3) until 30 million dry tons per decade. One interesting observation is the correlation between softwood marginal costs and aspen marginal costs. Marginal costs for softwoods increase rapidly after the 2010 decade—the decade in which aspen marginal costs begin to decrease. This increase can be explained by the fact that by the 2020 decade, aspen stands regenerated in the first period will be available for harvest; then, because the aspen market will no longer depend as much on mixed stands for harvest, the softwood market will have to absorb more of the costs of harvesting mixed stands or rely more heavily on the purer softwood stand types located farther from the market.

As expected, higher wood energy output levels for scenario 1 resulted in higher wood energy marginal costs (fig. 4). For all but the 30 million dry tons per decade level, wood energy marginal costs increase only slightly over time. Intuitively, one might expect a greater increase over time because of current species composition and imbalances in age distribution—that is, the forests of northeastern Minnesota now have a higher percentage of older trees and less desirable (wood energy) species than they will have in the second and subsequent rotations. A possible explanation for only a slight increase is that future rotations will contain more fully-stocked stands and thus more wood will be available in general. Another factor is that minimum rotation ages for strictly wood energy harvest were set quite high, thus making the current age distribution not as "imbalanced" in terms of wood energy use. Also, with any increase in wood energy marginal costs, the full-tree chipping operations are selected for more sites

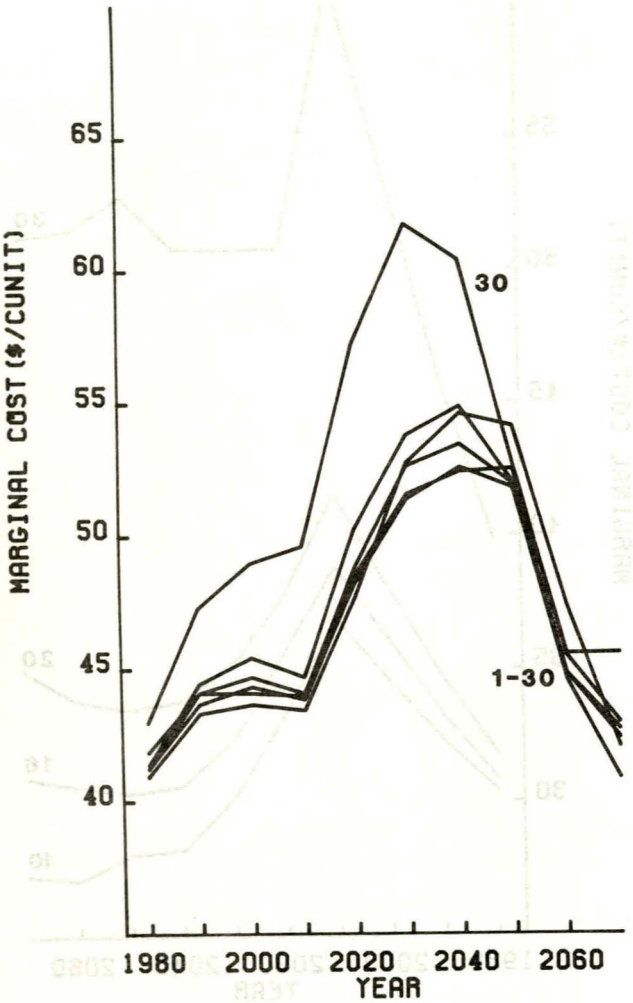

Figure 3.—*Softwood marginal cost estimates for different wood energy levels for scenario 1: aspen output constant, softwood output constant, and wood energy use continuing indefinitely. (Curve labels indicate the wood energy output level in millions of dry tons per decade.)*

and thus fewer stands are needed to meet the wood energy output levels.

Also of interest are the low wood energy marginal costs for low wood energy output levels (fig. 4). These low costs indicate a complementary relationship between wood energy and other forest products. Wood energy marginal cost estimates include both the direct per-unit cost of harvesting and transporting wood energy at the margin and the indirect impacts of that marginal unit on the production costs for other forest products. Based on the harvest and transport costs used in the study and assuming wood energy to be the only forest product, wood could be harvested and transported for about $13 per dry ton from stands located close to an energy market with low per dry ton harvest costs. But for low wood energy production levels (fig. 4) the wood energy marginal costs are lower than the

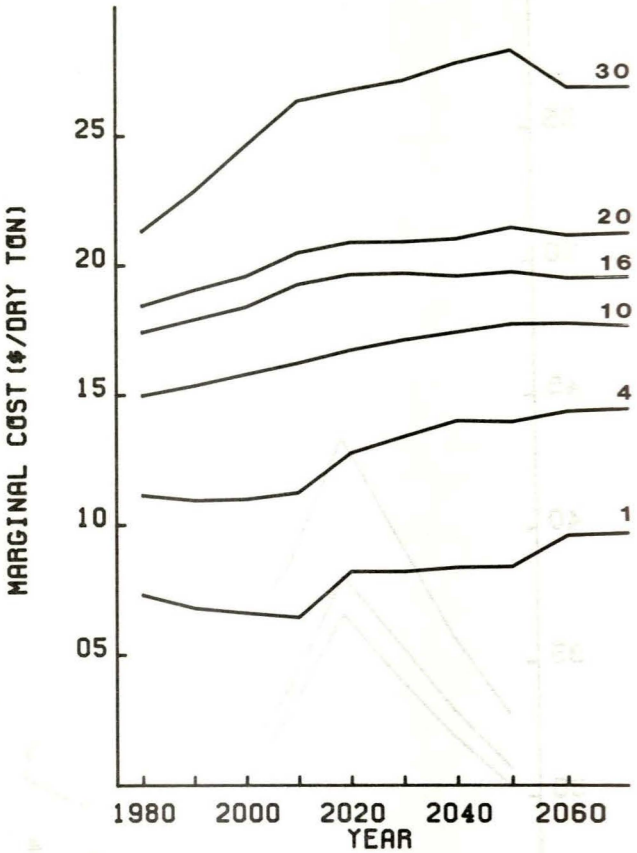

Figure 4.—*Wood energy marginal cost estimates for different wood energy levels for scenario 1: aspen output constant, softwood output constant, and wood energy use continuing indefinitely. (Curve labels indicate the wood energy output level in millions of dry tons per decade.)*

direct costs of harvesting and transporting even these low-cost stands; therefore, the indirect costs of wood energy on other products must be negative (complementary).

The results described to this point have all dealt with scenario 1: fixed and constant aspen and softwood output levels over time, and wood energy levels maintained throughout the planning horizon. As expected, softwood marginal costs are higher for scenarios that assume softwood outputs will increase over time, and aspen marginal costs are higher for scenarios that assume aspen outputs will increase over time. For all six scenarios, trends in the softwood marginal costs over time were similar to those for scenario 1 (fig. 3); and for wood energy levels up to 20 million dry tons per decade, softwood marginal costs are not sensitive to the wood energy level. Softwood marginal cost estimates do not increase even when the wood energy level is set at 30 million dry tons per decade for scenarios 3, 4, 5, and 6, the scenarios in which wood energy opportunities are considered as primarily short-term (30-year). In general, the relative insensitivity of softwood marginal

costs to wood energy output level is likely due to the fact that softwood harvests, even under the rising softwood output assumption, are well below potential levels.

Marginal cost estimates for wood energy depend on the assumption made about the future role of wood energy use. Figure 5 compares the wood energy marginal cost estimates for all six scenarios when wood energy level is set at 20 million dry tons per decade. For this level, as well as for other wood energy levels, the marginal cost curves fall into two groups: curves for scenarios that assume wood energy to be primarily a short-term (30-year) opportunity, and curves for scenarios that assume wood energy to be a long-term (100-year or more) opportunity. It is not surprising that marginal costs decrease for the 30-year scenarios soon after the wood energy output level drops. What is interesting is the similarity of the marginal costs within each group.

Marginal cost estimates for the aspen product group differ the most between scenarios. However, aspen marginal costs for scenario 2 are quite similar to those for scenario 1 (figs. 1 and 2). Aspen marginal costs for scenario 2 differ only in that they are lower for periods prior to period 5 (approximately $1 lower) if energy output levels are not above 10 million dry tons per decade, and they are higher for periods beyond period 5 (approximately $3 higher) if the energy output level is set at or above 20 million dry tons per decade. These slight differences can be explained by the differences in assumptions between scenarios 1 and 2: scenario 2 has the softwood output level rising over time while in scenario 1 it remains constant. If wood energy consumption is low, then increased softwood consumption could complement aspen production in the short run in a way similar to the complementary impact of increased wood energy consumption on aspen for lower wood energy levels. At higher wood energy levels, the short-run complementary impact on aspen from rising softwood consumption would not be as great because much of the complementary impact could be achieved through the harvesting for wood energy. Rising softwood consumption could obviously have a long-run competitive effect on aspen because of the rising need for land to grow (regenerate) softwoods; the comparison between scenario 1 and 2 shows the effect would be greater when timber consumption in general is higher.

Aspen marginal cost estimates for scenario 3 are similar to those for scenario 4 (fig. 6). The general shapes of the curves are similar to the shapes found in the first two scenarios. The major differences are that the marginal costs are not quite as sensitive to the wood energy output level and that marginal costs are not as high for high wood energy levels. These types of results

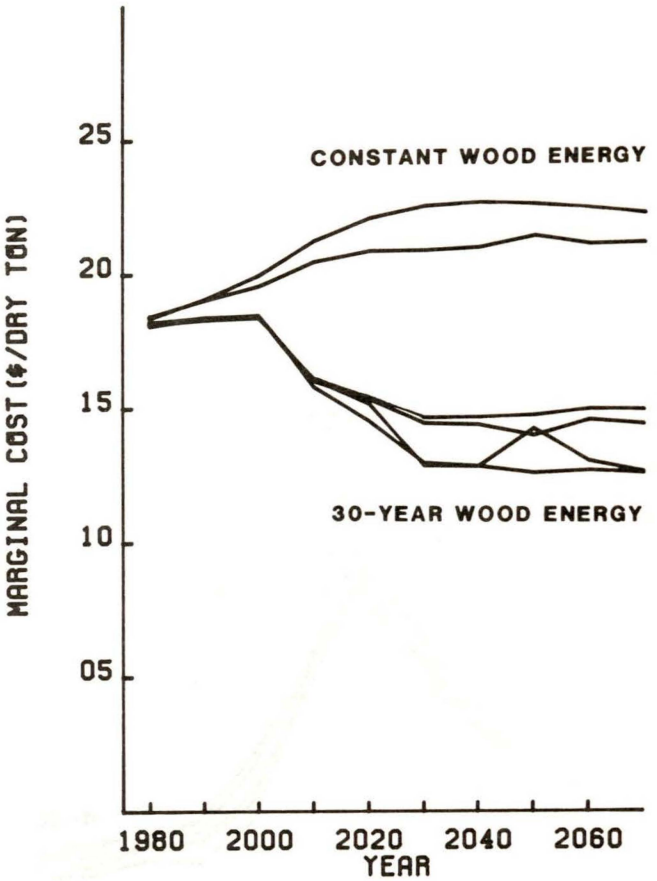

Figure 5.—*Wood energy marginal cost estimates for each of the six scenarios when wood energy output is 20 million dry tons per decade. (Each curve represents a different scenario.)*

would be expected from these two scenarios because they consider wood energy use as primarily a short-term opportunity.

Scenarios 5 and 6 have similar aspen marginal cost estimates. For these scenarios, aspen output levels are rising over time. Figure 7, which portrays the aspen marginal cost estimates for scenario 5, shows a definite advantage in the long run for higher wood energy output levels; higher wood energy output levels have lower aspen marginal costs in all periods beyond 2010. This complementary impact of wood energy use on aspen must be due to the fact that many stands will regenerate naturally after harvest to a stand with an even greater aspen component. The complementary impact is greater for scenarios 5 and 6 because these are the scenarios in which future aspen consumption is greatest. Another interesting point from figure 7 is that even with increased wood energy harvesting in the short run, aspen marginal costs in the short run do not increase significantly until the wood energy output level rises above the 30 million dry tons per decade level.

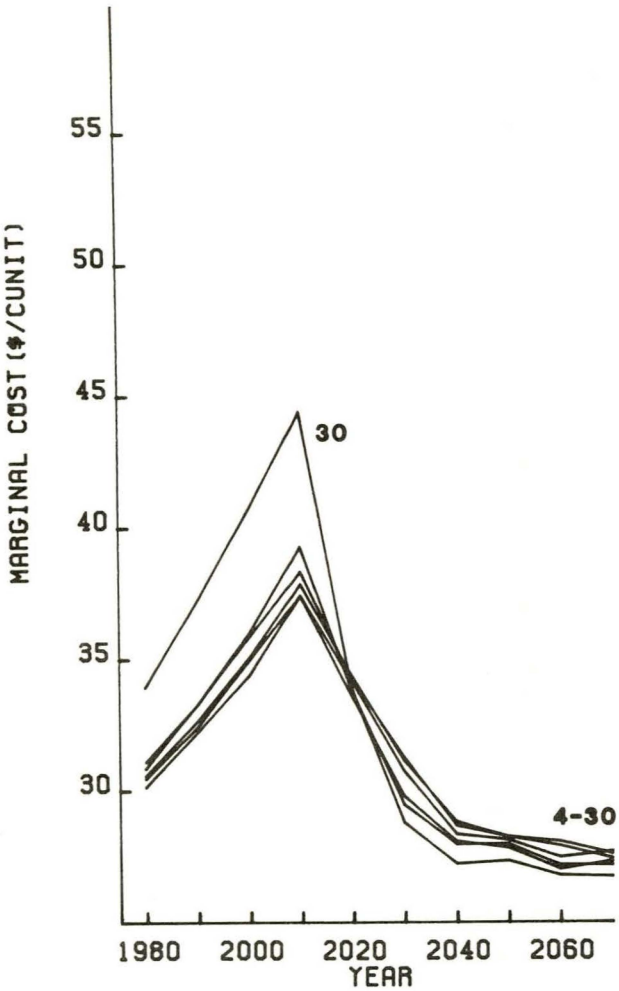

Figure 6.—*Aspen marginal cost estimates for different wood energy levels for scenario 3: aspen output constant, softwood output constant, and wood energy use primarily a 30-year opportunity. (Curve labels indicate the wood energy output level in millions of dry tons per decade per year.)*

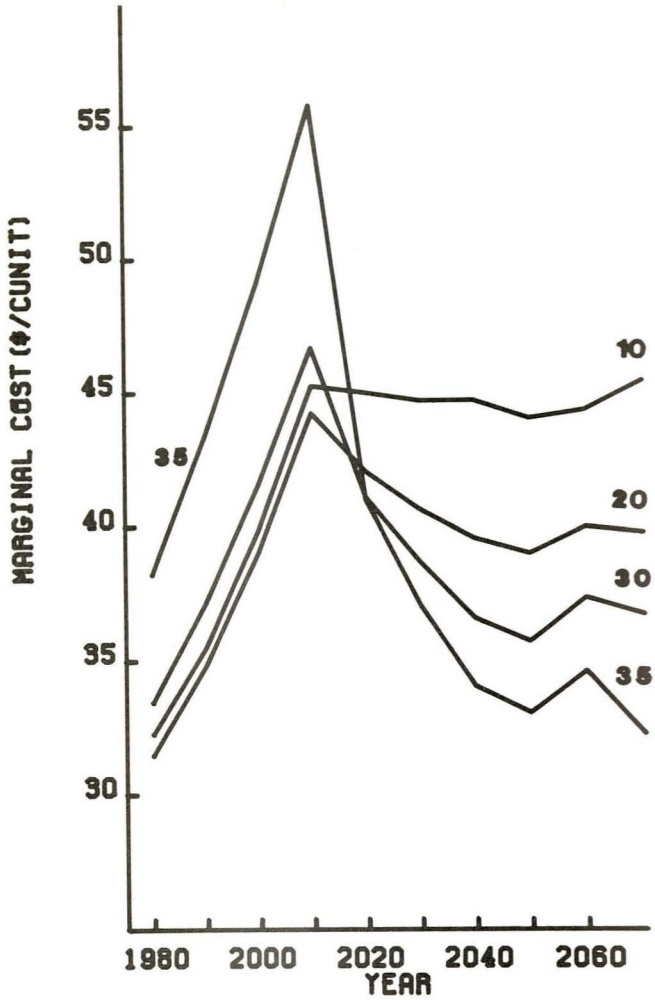

Figure 7.—*Aspen marginal cost estimates for different wood energy levels for scenario 5: aspen output increasing after 40 years, softwood output constant, and wood energy primarily a 30-year opportunity. (Curve labels indicate the wood energy output level in millions of dry tons per decade per year.)*

Least Cost Management Schedules

A major concern with wood energy use is the type of wood that would actually be burned. Obviously the surplus dense hardwoods are well suited for energy production, but stand locations or harvest cost considerations might make it advantageous to burn other species. For scenario 1 almost all of the wood energy at the lower levels of wood energy use is supplied from the other-hardwood category over the entire planning horizon (fig. 8). At higher levels of use more wood energy is supplied from the aspen and softwood categories. A significant portion of this wood, however, is likely to be tops and limbs that would be chipped in chip and sort operations. Unfortunately, the model was not structured to identify the quantities of aspen or softwood roundwood that would be burned.

Looking at just period 1 schedules gives us an idea of what should be done today. The scenario 1 summary for period 1 (fig. 9) shows even higher percentages of wood energy coming from hardwoods than the scenario 1 summary for the entire planning horizon. Even at high levels of wood energy consumption only small percentages are supplied from the aspen and softwood categories. These statistics are somewhat misleading, however, in that one would not expect any evidence, like that shown earlier, of a competitive impact between wood energy use and other timber uses if significant volumes of other products are not burned. Significant volumes are burned at higher wood energy levels because even though the actual percentages are low, the wood energy levels are high enough to make even small percentages significant (fig. 10).

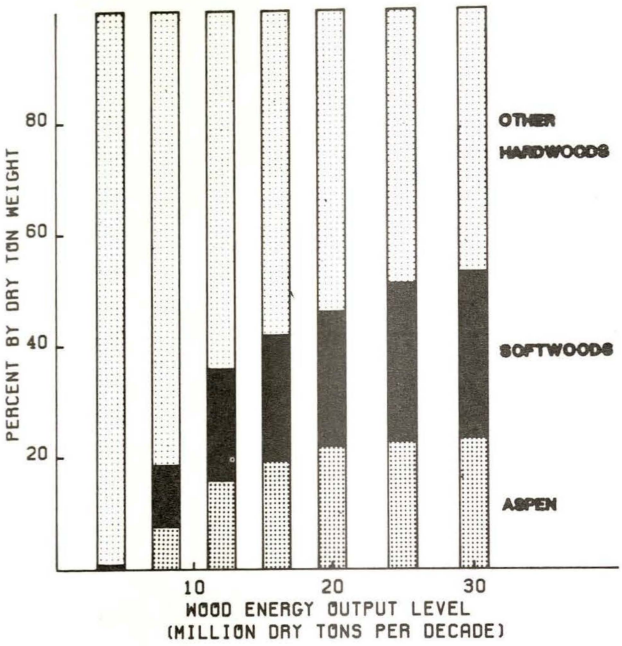

Figure 8.—*Species group breakdown of wood energy consumption for the entire planning horizon as scheduled for different wood energy output levels for scenario 1.*

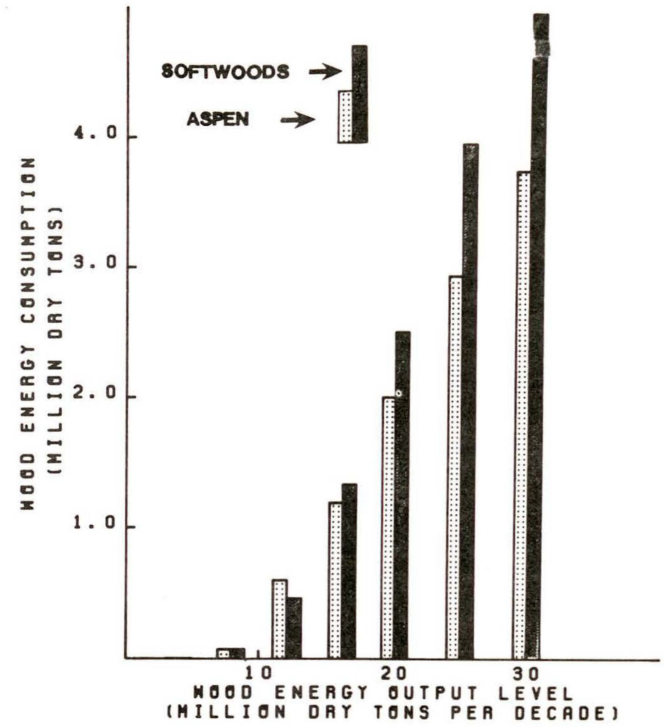

Figure 10.—*Aspen and softwood consumed as wood energy during period 1 as scheduled for different wood energy output levels for scenario 1.*

Another important factor is the form in which wood is harvested for energy use. In this study no value differential was assumed for the form in which wood energy is delivered to the user. Most residential users prefer roundwood, but the larger commercial users prefer chips. Based on the no value differential assumption the form in which wood energy would be delivered is quite sensitive to the wood energy output level (fig. 11). At low output levels, traditional roundwood operations are favored as there is plenty of wood to meet all uses without concern about leaving burnable material in the

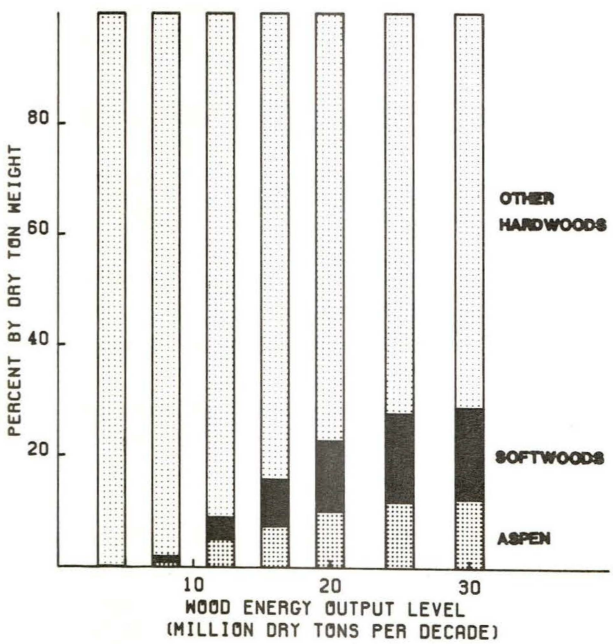

Figure 9.—*Species group breakdown of wood energy consumption for period 1 as scheduled for different wood energy output levels for scenario 1.*

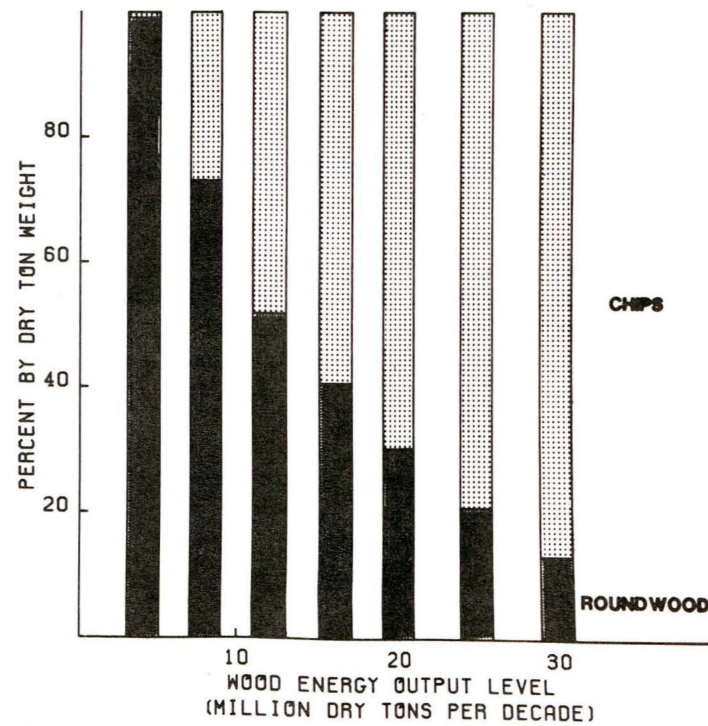

Figure 11.—*Method of harvest breakdown over all periods for wood energy consumption as scheduled for different wood energy output levels for scenario 1.*

woods. These results might be quite different, however, if a value differential were assumed between roundwood and chips.

Selecting a Wood Energy Consumption Level

The supply cost interactions examined earlier give an indication of the impacts of wood energy use on the supply costs for other forest products, but the optimum wood energy production level is not necessarily the level at which the net positive impact on other timber consumers is maximized. Identifying and quantifying impacts on other timber consumers is important only to the extent that this information can be helpful in developing policies to help allocate both the benefits and costs of a wood energy development program. From a strict production economics viewpoint, the optimal wood energy production level is still the level at which marginal revenue from wood energy equals marginal cost where both direct and indirect revenues and costs are recognized. If there are equity problems at this level, policies should be sought that can help redistribute impacts.

Identifying the production level where marginal cost equals marginal revenue is difficult, because both revenues and costs are hard to measure. Revenues generated from today's regeneration actions will not be received for many years; in the interim, timber prices can change significantly. Impacts of activities on nonmarket resources, such as wildlife, water, and recreation, are also difficult to measure. However, increased timber use in northeastern Minnesota would probably not be detrimental to nonmarket forest resources unless the increase were quite substantial. Significant costs the analysis did not recognize include sales administration and road construction. Obviously, roads serve many purposes, and allocating all road costs to timber production does not seem appropriate. Road costs are also difficult to incorporate into a timber scheduling model because a single road often serves many stands, thus making it difficult to assign road costs to a specific alternative for a specific stand.

From a regional perspective, the impact of forestry activities on the economy can be enormous. Undoubtedly, increased harvest means increased jobs, and northeastern Minnesota is currently suffering high unemployment. Viewed in this light, it would seem that the more wood energy use the better. But future wood industry expansion opportunities could be affected by the amount of wood allocated to wood energy today. Wood-using industries based on new technologies could plausibly materialize, producing a much greater economic impact on the region than wood energy. Developing strategies for wood energy development is thus an issue that needs attention from the political arena.

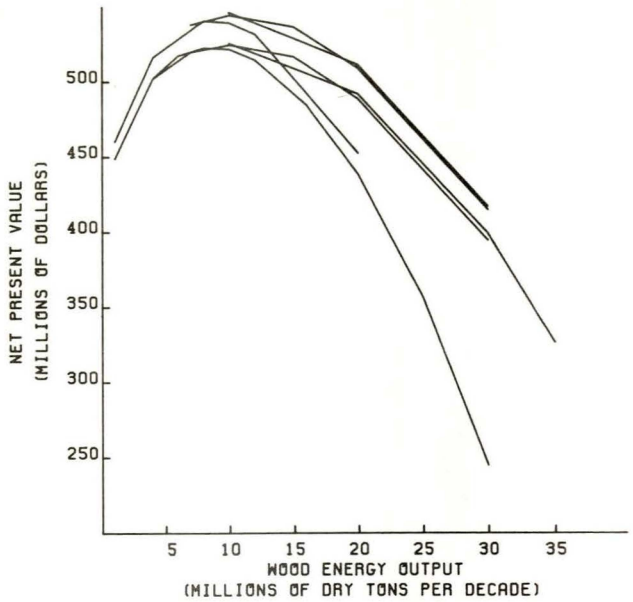

Figure 12.—*Net present worth estimates for the schedules developed for each scenario assuming that the wood energy, as produced, is worth $15 per dry ton. (Each curve represents a different scenario.)*

As part of the analysis, the NPW of each schedule produced was estimated once for each of two different sets of assumptions describing future product prices. These sets all assumed constant real prices over time and differed only in the assumptions made concerning the price of wood energy. The two wood energy prices considered were $15 and $25 per dry ton. The absolute magnitude of each NPW estimate is extremely sensitive to the prices assumed. Of real interest is a comparison of the NPW's for alternative levels of wood energy production for each set of price assumptions.

Figure 12 compares the NPW estimates for the assumption that wood energy is worth $15 per dry ton. Each curve represents one of the six scenarios considered. For each scenario and this wood energy price assumption, NPW is maximized at approximately the 12 million dry tons per decade level. As discussed earlier, this wood energy production level could complement production of other timber products.

Figure 13 compares the NPW estimates for the assumption that wood energy is worth $25 per dry ton. As in figure 12, each curve represents one of the six scenarios. For each scenario and this wood energy price assumption, NPW is maximized at the highest wood energy consumption level examined. This suggests there is a large opportunity cost of not better utilizing the timber resource. For example, the NPW for the 30 million dry tons per decade level exceeds the NPW for the 10 million dry tons per decade level by approximately $300 million. The continuously increasing NPW

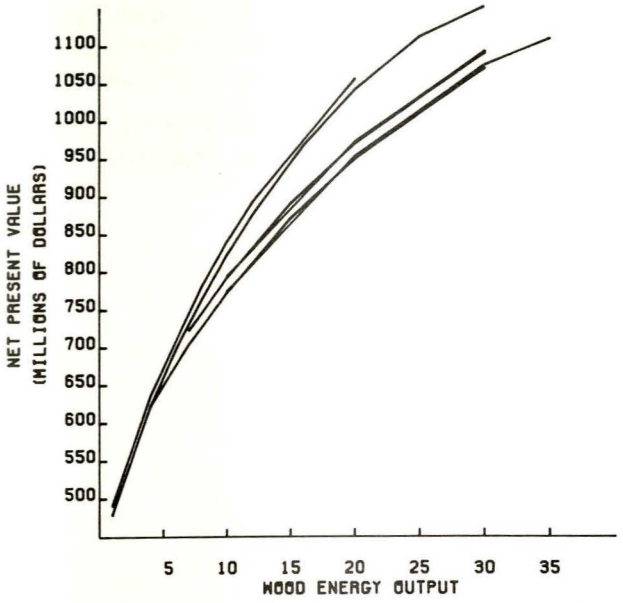

Figure 13.—*Net present worth estimates for the schedules developed for each scenario assuming that the wood energy, as produced, is worth $25 per dry ton. (Each curve represents a different scenario.)*

values with higher wood energy levels suggest that even higher wood energy levels be considered. However, for the silvicultural systems considered, consumption levels could not be increased significantly without reaching the maximum biological limit.

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Table 2.--Output levels considered for the aspen product group and the softwood product group

(In thousands of cunits per decade)

Period midpoint year	Aspen		Softwood	
	Constant output trend	Increasing output trend	Constant output trend	Increasing output trend
1980	5,500	5,500	4,000	4,000
1990	7,000	7,000	4,000	4,500
2000	7,000	7,000	4,000	4,500
2010	7,000	7,000	4,000	5,500
2020	7,000	7,500	4,000	6,000
2030	7,000	8,000	4,000	6,500
2040	7,000	8,500	4,000	7,000
2050	7,000	9,000	4,000	7,500
2060	7,000	9,000	4,000	7,500
2070	7,000	9,000	4,000	8,000

Table 3.--Marginal costs of production for alternative wood energy production levels for scenario 1: aspen output constant, softwood output constant, and wood energy use continuing indefinitely

Period midpoint year	Ten-year wood energy production level (Millions of dry tons)									
	1	4	6	8	10	12	16	20	25	30
	ASPEN (Dollars per cunit)									
1980	33.11	31.11	30.58	30.22	30.41	30.44	30.84	31.79	34.56	39.74
1990	36.06	33.28	32.54	32.09	32.29	32.41	33.22	34.59	38.62	45.93
2000	39.77	35.83	34.69	34.11	34.49	34.59	36.04	38.00	43.95	53.49
2010	43.51	38.32	36.81	36.28	36.89	37.14	38.86	41.56	49.36	60.92
2020	38.81	34.19	33.15	33.02	33.33	33.95	35.63	37.68	43.71	50.82
2030	35.87	31.25	30.08	29.89	30.18	30.61	32.33	35.16	42.55	50.77
2040	32.99	28.65	28.27	28.32	28.19	28.41	30.62	33.80	41.57	50.86
2050	30.47	28.22	27.97	28.21	28.05	28.27	30.35	33.51	40.66	52.84
2060	29.88	27.88	27.09	27.17	27.10	27.69	30.64	33.88	40.78	51.59
2070	30.91	27.40	27.29	27.29	27.32	27.64	31.00	35.04	41.02	51.35
	SOFTWOODS (Dollars per cunit)									
1980	40.96	41.86	41.25	41.37	41.25	41.05	41.24	41.38	41.69	42.98
1990	43.32	44.09	43.67	43.52	43.68	43.61	44.09	44.44	45.05	47.28
2000	43.66	44.08	44.06	44.04	44.32	44.18	44.69	45.41	46.19	48.96
2010	43.43	43.96	43.74	43.75	43.83	43.40	44.05	44.68	45.65	49.60
2020	47.68	48.47	47.85	48.22	48.21	48.02	48.79	50.22	50.43	57.22
2030	52.73	51.55	51.19	51.56	51.36	51.25	52.60	53.76	54.72	61.73
2040	54.57	52.39	52.20	52.54	52.54	52.86	53.42	54.84	55.29	60.37
2050	54.09	52.50	52.11	51.18	51.76	51.90	51.91	51.97	53.43	52.66
2060	47.39	45.44	45.04	44.31	44.55	45.07	44.77	44.77	46.12	45.52
2070	42.03	42.94	41.90	41.81	40.84	40.70	42.35	42.67	45.99	45.54
	WOOD ENERGY (Dollars per dry ton)									
1980	7.30	11.12	13.13	14.04	14.98	15.86	17.41	18.43	19.68	21.32
1990	6.78	10.92	13.02	14.20	15.35	16.42	17.90	19.03	20.61	22.83
2000	6.59	10.97	13.27	14.52	15.78	16.95	18.38	19.56	21.70	24.59
2010	6.42	11.22	14.04	15.20	16.21	17.48	19.24	20.46	22.94	26.31
2020	8.19	12.73	14.86	15.49	16.69	17.96	19.60	20.84	23.39	26.70
2030	8.18	13.35	15.10	15.90	17.07	18.20	19.64	20.85	23.60	27.06
2040	8.34	13.95	15.52	16.41	17.36	18.16	19.51	20.95	23.76	27.72
2050	8.36	13.90	15.82	16.71	17.66	18.34	19.66	21.38	24.06	28.18
2060	9.56	14.29	15.74	16.71	17.67	18.22	19.40	21.05	23.20	26.72
2070	9.63	14.37	15.97	16.89	17.54	18.21	19.41	21.09	23.31	26.67

Table 4.--Marginal costs of production for alternative wood energy production levels for scenario 2: aspen output constant, softwood output increasing, and wood energy use continuing indefinitely

Period midpoint year	Ten-year wood energy production level (Millions of dry tons)					
	1	4	8	10	12	20
	ASPEN (Dollars per cunit)					
1980	32.26	30.08	29.46	29.04	29.23	32.10
1990	34.69	31.76	30.85	30.25	30.50	35.11
2000	37.53	33.38	32.25	31.63	32.05	39.06
2010	40.60	34.99	33.96	33.22	33.89	43.15
2020	36.45	32.28	31.76	31.39	32.10	40.86
2030	33.84	29.29	29.08	28.85	29.19	39.20
2040	31.52	28.08	28.17	27.66	28.17	37.86
2050	29.38	28.24	27.97	27.89	28.60	37.61
2060	29.22	27.47	27.33	26.84	27.88	36.64
2070	29.64	28.05	27.52	27.17	28.55	38.50
	SOFTWOODS (Dollars per cunit)					
1980	43.24	43.47	43.04	43.15	43.20	43.47
1990	46.99	47.10	46.41	46.78	46.80	47.81
2000	48.71	48.52	47.98	48.65	48.38	49.77
2010	50.20	49.99	48.85	49.28	49.13	50.66
2020	55.50	54.07	52.59	53.08	53.13	55.28
2030	58.87	57.16	56.05	56.58	56.65	58.71
2040	59.70	57.80	56.76	57.37	57.57	59.56
2050	57.32	55.85	53.21	52.71	52.65	52.57
2060	50.04	48.88	46.74	46.18	46.05	46.20
2070	45.44	44.35	42.82	42.46	41.96	43.85
	WOOD ENERGY (Dollars per dry ton)					
1980	6.65	10.43	14.01	14.92	15.84	18.37
1990	6.35	10.38	14.15	15.37	16.44	19.07
2000	6.14	10.34	14.62	15.85	17.05	19.95
2010	6.17	10.66	15.30	16.33	17.65	21.24
2020	7.53	12.56	15.96	16.96	18.18	22.07
2030	7.92	13.45	16.45	17.45	18.52	22.50
2040	8.23	14.08	16.96	17.88	18.70	22.62
2050	8.35	14.63	17.12	17.87	18.73	22.54
2060	9.53	14.65	17.08	17.81	18.34	22.39
2070	9.62	14.63	17.13	17.80	18.22	22.18

Table 5.--Marginal costs of production for alternative wood energy production levels for scenario 3: aspen output constant, softwood output constant, and wood energy use primarily a 30-year opportunity

Period midpoint year	Ten-year wood energy production level (Millions of dry tons)					
	4	7	10	15	20	30
	ASPEN (Dollars per cunit)					
1980	31.11	30.59	30.47	30.15	30.86	33.93
1990	33.28	32.65	32.42	32.22	33.27	37.20
2000	35.83	35.05	34.93	34.38	35.97	40.68
2010	38.32	37.84	37.41	37.40	39.27	44.39
2020	34.19	34.30	34.11	33.52	33.74	33.77
2030	31.25	31.12	30.71	29.76	29.44	28.76
2040	28.65	28.79	28.32	28.05	27.95	27.21
2050	28.22	28.22	28.11	27.81	27.95	27.32
2060	27.88	28.05	27.45	27.00	27.15	26.76
2070	27.40	27.59	27.66	27.30	27.16	26.71
	SOFTWOODS (Dollars per cunit)					
1980	41.86	40.73	40.35	40.84	40.48	40.34
1990	44.09	42.90	42.42	43.36	42.89	43.03
2000	44.08	43.20	42.73	43.86	43.48	43.44
2010	43.96	42.86	42.58	43.34	43.26	43.65
2020	48.47	46.81	46.70	47.59	48.07	49.10
2030	51.55	51.14	51.16	50.98	51.74	52.31
2040	52.39	52.75	52.59	51.74	52.21	52.37
2050	52.50	51.86	51.64	51.40	50.44	49.30
2060	45.44	45.13	44.65	44.37	43.53	42.49
2070	42.94	40.61	39.69	41.15	41.02	40.80
	WOOD ENERGY (Dollars per dry ton)					
1980	11.12	13.63	14.80	16.72	18.21	20.03
1990	10.92	13.56	15.04	16.90	18.37	20.57
2000	10.97	13.53	15.11	16.94	18.46	20.90
2010	11.22	13.49	14.32	15.50	15.99	16.67
2020	12.73	13.83	14.55	15.08	15.31	15.62
2030	13.35	13.81	13.91	14.36	14.40	14.77
2040	13.95	13.37	13.42	14.08	14.34	14.64
2050	13.90	13.35	13.42	13.78	13.93	14.30
2060	14.29	13.58	13.68	14.30	14.51	14.50
2070	14.37	13.88	13.85	14.43	14.34	14.70

Table 6.--Marginal costs of production for alternative wood energy production levels for scenario 4: aspen output constant, softwood output increasing and wood energy use primarily a 30-year opportunity

Period midpoint year	Ten-year wood energy production level (Millions of dry tons)				
	7	10	15	20	30
	ASPEN (Dollars per cunit)				
1980	29.72	29.31	29.31	29.85	33.26
1990	31.27	30.65	30.81	31.75	36.15
2000	33.02	32.24	32.38	33.69	39.30
2010	35.05	34.21	34.84	36.46	42.41
2020	32.39	31.96	32.06	32.73	33.58
2030	29.25	28.79	28.94	28.92	29.16
2040	28.02	27.83	27.68	27.73	27.18
2050	28.15	27.88	27.75	27.90	27.66
2060	27.33	27.07	26.92	27.13	26.86
2070	27.78	27.53	27.35	27.12	26.53
	SOFTWOODS (Dollars per cunit)				
1980	42.99	42.73	42.85	42.68	43.56
1990	46.19	45.94	46.40	46.23	47.57
2000	47.38	47.44	47.78	47.47	48.95
2010	48.22	47.89	48.38	48.07	50.33
2020	52.26	51.87	51.88	51.56	53.66
2030	55.95	55.50	55.37	54.94	56.52
2040	56.60	56.27	55.56	54.86	54.49
2050	54.00	53.04	51.79	50.23	47.53
2060	47.38	46.37	45.77	44.40	42.18
2070	42.26	41.24	41.14	42.08	42.17
	WOOD ENERGY (Dollars per dry ton)				
1980	13.25	14.71	16.50	18.08	20.15
1990	13.14	14.95	16.92	18.36	20.80
2000	13.35	15.19	16.96	18.41	21.31
2010	13.25	14.61	15.35	16.10	17.32
2020	13.85	14.74	15.23	15.40	16.18
2030	13.82	14.36	14.47	14.61	15.05
2040	14.04	14.10	14.35	14.62	15.33
2050	13.87	14.26	14.37	14.69	14.98
2060	14.17	14.47	14.61	14.91	15.12
2070	14.45	14.51	14.61	14.87	15.00

Table 7.--Marginal costs of production for alternative wood energy production levels for scenario 5: aspen output increasing after 40 years, softwood output constant, and wood energy use primarily a 30-year opportunity

Period midpoint year	Ten-year wood energy production level (Millions of dry tons)			
	10	20	25	30
	ASPEN (Dollars per cunit)			
1980	32.23	31.44	33.40	38.20
1990	35.45	34.76	37.09	43.31
2000	39.83	38.99	41.50	49.07
2010	45.21	44.19	46.64	55.73
2020	44.94	41.99	41.03	40.95
2030	44.62	40.56	38.61	37.01
2040	44.62	39.47	36.51	33.98
2050	43.93	38.89	35.63	32.97
2060	44.25	39.90	37.27	34.54
2070	45.33	39.66	36.64	32.20
	SOFTWOODS (Dollars per cunit)			
1980	38.51	39.39	38.75	39.65
1990	40.10	41.71	41.09	42.52
2000	39.86	41.91	41.21	42.71
2010	39.64	41.46	40.84	42.98
2020	42.97	45.12	44.76	48.70
2030	47.64	49.51	49.32	51.67
2040	50.39	50.54	49.85	51.50
2050	51.42	49.89	48.76	48.06
2060	46.84	43.19	42.89	41.74
2070	44.81	43.53	42.84	41.63
	WOOD ENERGY (Dollars per dry ton)			
1980	14.51	18.16	19.90	21.73
1990	14.69	18.40	20.44	22.65
2000	14.77	18.44	20.75	23.28
2010	13.87	15.77	16.22	16.90
2020	13.87	14.49	14.63	14.70
2030	12.79	12.92	12.96	13.44
2040	12.61	12.80	12.89	13.40
2050	12.53	12.53	12.52	13.23
2060	12.66	12.63	12.45	12.66
2070	12.54	12.52	12.59	13.35

Table 8.--Marginal costs of production for alternative wood energy production levels for scenario 6: aspen output increasing after 40 years, softwood output increasing, and wood energy use primarily a 30-year opportunity

Period midpoint year	Ten-year wood energy production level (Millions of dry tons)		
	10	20	30
	ASPEN (Dollars per cunit)		
1980	29.57	30.16	34.03
1990	31.31	32.51	37.77
2000	33.69	35.80	42.18
2010	37.52	39.92	46.88
2020	38.90	38.55	39.98
2030	38.90	37.60	37.16
2040	40.07	36.78	34.62
2050	40.52	36.24	34.56
2060	40.96	37.38	36.03
2070	42.02	36.98	34.27
	SOFTWOODS (Dollars per cunit)		
1980	42.04	42.48	42.85
1990	45.13	46.00	46.84
2000	46.11	47.24	48.08
2010	46.68	47.91	49.38
2020	50.95	51.75	53.57
2030	55.31	55.57	55.99
2040	56.13	56.00	55.05
2050	52.30	48.87	48.40
2060	46.13	43.15	42.71
2070	44.19	43.95	44.86
	WOOD ENERGY (Dollars per dry ton)		
1980	14.54	18.13	20.25
1990	14.79	18.30	20.98
2000	14.93	18.38	21.57
2010	14.14	16.04	17.18
2020	13.93	15.14	14.89
2030	12.86	12.83	13.55
2040	12.59	12.79	14.05
2050	13.01	14.21	13.87
2060	12.68	12.98	13.10
2070	12.69	12.57	13.57

AN ASSESSMENT OF PRODUCTIVITY AND HARVESTING COSTS FOR VARIOUS FOREST HARVEST SYSTEMS

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Forest residues are increasingly important to forest industry and other economic sectors as well. In northern Minnesota, an area heavily forested and almost totally dependent upon imported fuels, forest residues are a valuable fuel. As part of an effort to analyze the alternatives and opportunities for partially replacing fossil fuels with forest residues in northeastern Minnesota, it was necessary to develop harvest system production and cost data for the Lake States region, emphasizing harvest systems handling small stems and/or logging residues. We extensively reviewed literature dealing with available small log harvest systems, and compiled production and cost data for eight selected harvesting systems. New and used equipment configurations were investigated, with costs calculated per cunit and per million Btu.

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LITERATURE SUMMARY

Generalized conclusions based on an extensive review of literature are as follows:

1. Forest access and tract size characteristics of a stand can limit the type of harvesting system that may be utilized. Generally, if a stand is under 30 acres in size, manual systems are more economical. Most mechanical systems do not reach their minimum cost levels until a tract size of 60-80 acres is attained.

2. Stand volume and average stem diameter are critical factors affecting production and costs, no matter what harvesting system is used. Conventional and integrated systems often require an average d.b.h. of 6-10 inches with expected yields of at least 30-50 tons per acre to be economical. Manual techniques have generally been found to be more economical than mechanical systems in small diameter stands (3-5 inches).

3. In pre- and post-harvesting residue systems, the size of the residue pieces is often the limiting factor. Most studies indicate that pieces averaging less than 2-5 cubic feet are not economical.

4. When logging for conventional products, a highly mechanized, full-tree harvest system is one of the most economical operations. In comparison, manual tree-length systems are more costly (but have lower fixed costs), and are comparable to stump bobtail and shortwood prehauler systems. Full-tree (rather than tree-length) skidding is recommended wherever possible.

5. Many types of highly mechanized operations, with high investment costs, require a high machine utilization rate (generally greater than 60 percent) to function efficiently. This is especially critical for feller-bunchers and whole-tree chippers.

6. For a highly mechanized/high production whole-tree chipping operation operating at woods landing, under optimum conditions, an average (delivered) cost per green ton of $12.31 (1980 dollars) was indicated. Average chip production cost ranged from $9 to a high of $15 per green ton; varying daily production rates were responsible for the cost differences.

7. In most cases, chipping at the harvesting site (woods landing) is more economical than chipping at a central landing, and is comparable to chipping at a mill. Debarking and chipping in the woods appears to be too costly compared to debarking at the mill and is not recommended.

8. A central processing yard (CPY) system offers definite advantages compared to a conventional system. One of the most important is that an increased volume of material is generated which may be used as wood fuel. This increased utilization can offset the higher costs associated with a CPY.

9. Integrated operations that produce conventional roundwood products and whole-tree chips for energy or pulp can be economical. However, the production and sorting of roundwood must not interfere with chip production. For a low cost integrated system, a four-person crew with a medium-sized chipper may have the most potential.

10. Pre-harvesting unmerchantable material for fuelwood has the advantages of potentially increasing conventional harvest productivity and reducing the time and costs of site preparation and regeneration.

11. The economics of post-logging operations which harvest logging residues and residual trees is highly dependent on the volume and size of the biomass. Bunching residues can lower collection costs significantly. Equipment best suited for residue harvest are feller-skidders in large residual trees and low grade stands, and forwarders equipped with a wide trailer and grapple saw, for gathering logging residues that are on the ground. Costs varied considerably between residue harvest studies involving different equipment mixes. Costs ranged from $32 to $75 (1978 dollars) per ODT.

12. Since most harvesting research is limited to a small set of sites, situations, and economic, and environmental constraints, it should be evaluated with caution.

PRODUCTION AND COST DATA FOR 8 HARVEST SYSTEMS

Harvesting Operations

Eight harvesting systems were evaluated to determine production capacity and costs per cunit when operating in typical northern Minnesota forest stands. The harvesting systems included whole-tree chip, whole-tree chip with saw log sort, tree-length logging and tree-length with chipping, and mechanized fell-/manual buck harvesting systems. Table 1 summarizes equipment and labor configurations for each system.

Investment costs for these systems were found to range from $300,000 for the mechanized fell/manual buck system to almost $1 million for the tree-length/chipping system (1983 dollars). Investment costs were based on new equipment unless otherwise specified. Total capital investment costs are listed in table 1.

Production and Cost Inputs

Production rates for individual machines were collected from current literature sources and from equipment manufacturers. These rates were used to determine overall harvest system productivity. Production rates were developed for a range of basal areas (20-140 ft^2/acre) and diameters at breast height (5, 6, 8, 10, and 12 inches) for northern Minnesota aspen stands. All harvests were assumed to be clearcuts on gently sloping terrain.

Machine costs were developed according to methods described by Miyata (1980). Fixed and operating costs per productive hour[3] were calculated for each machine. Straight line depreciation and an 11.5 percent interest rate were used in the machine rate calculations. Machine and labor utilization rates were assumed to be at average rates (no unusual delays or downtime). Labor

[3] *According to Miyata, a productive hour is that part of scheduled operating time during which a machine actually operates which is based on the machines estimated utilization rate. A scheduled hour is the time during which equipment is scheduled to do productive work.*

Table 1.--Equipment investment cost and personnel requirements for 8 harvest systems

Equipment	Tree-length logging/ chipping	22" Whole-tree sort/chip	22" Whole-tree chip	Mechanized fell/manual buck (3)1/	Mechanized tree-length logging	Mechanized fell/manual buck (2)1/	18" Whole-tree chip/sort	18" Whole-tree chip
Hahn pulp/logger II limber/slasher	1				1			
Timber jack 30 feller buncher	2	2	2	1	1	1	1	1
John Deere 640 grapple skidder	2	2	2	1	1	1	1	1
22" morbark chipper		1	1					
18" trelan chipper	1						1	1
Cat D40 dozer/skidder (used)	1	1	1	1	1	1	1	1
Chainsaw	2	2	2	8	2	6	2	2
Crew truck	1	1	1	1	1	1	1	1
Maintenance truck (used)	1	1	1	1	1	1	1	1
Fuel truck (used)	1	1	1	1	1	1	1	1
Lowboy (used)	1	1	1	1	1	1	1	1
Total Capital Investment (1983 dollars)	916,803	752,803	752,803	297,177	569,183	296,179	418,183	418,183
Total crew size	9	8	7	10	6	8	5	6

1/ (3) refers to 3 delimber/toppers and 3 buckers
(2) refers to 2 delimber/toppers and 2 buckers

Table 2.--Harvest system cost per productive hour

System	Machine cost	(Percent of total)	Labor cost	(Percent of total)	Total system cost
Tree-length logging/chipping	286.53	(63)	168.62	(37)	455.15
22" Whole-tree chip/sort	237.54	(63)	141.25	(37)	378.79
22" Whole-tree chip	237.54	(66)	125.06	(34)	362.60
Mechanized fell/manual buck (3)	121.08	(40)	182.28	(60)	303.36
Mechanized tree-length logging	166.72	(61)	107.54	(39)	274.26
Mechanized fell/manual buck (2)	113.38	(44)	145.28	(56)	258.66
18" Whole-tree chip/sort	138.66	(56)	108.28	(44)	246.94
18" Whole-tree chip	138.66	(61)	89.78	(39)	228.44

costs include a base rate of $10.25 (foreman) or $9.25 (laborer) and a benefit package of 40 percent.

Harvesting system costs per productive hour include machine and labor costs (table 2). These figures do not include product transportation costs to the mill, road building costs, stumpage costs, or production quotas.

Each system was assumed to operate 250 days a year for 9 hours each day, giving an estimated 2,250 scheduled hours per year. Total productive hours vary with each machine and system. The large, highly mechanized systems (tree length logging/chipping and 22 inch WTC/sort) were the most expensive per productive hour (up to twice as much compared to the smaller or less mechanized systems, mechanized fell/manual buck and 18 inch WTC).

Harvest System Cost Analysis

Costs per cunit per productive hour were calculated for each harvest system and are summarized in table 3 to compare harvesting systems. The system found to have the highest average cost per cunit is tree length logging/chipping ($42.38). The 18-inch whole-tree chip system ($28.56) is lowest; because of reported problems with small sized chippers due to jamming and to large crowns, the assumed utilization rate for this unit may be unrealistically high (and thus the cost of $28.56 may be a bit low). Assuming that the $28.56 figure is accurate, the harvesting cost for the 22-inch WTC averages $7.38 more per cunit than the 18-inch WTC, due to the high cost of a new chipper. The higher production of a 22-inch system is not enough to compensate for its much higher capital investment.

All systems were extremely sensitive to stand variables. Costs decreased as basal area and/or average diameters increased.

Used Equipment Cost

High investment costs associated with new equipment increase cost per cunit. Most logging firms today utilize used machinery. To investigate the effect of used equipment on cost per cunit data, four systems were reconstructed using used machinery prices. The 22-inch whole-tree chipping, 22-inch WTC with sort, tree-length logging with chipping, and 18-inch whole-tree chipping systems were selected. The new and used equipment prices include total system investment costs (table 4). Total system ivestment costs were lowered by as much as 42 percent.

Used equipment investment costs were used to calculate harvest system cost per productive hour (table 5). Estimates were obtained from equipment dealers in the Lake States and are applicable only to this region. Used equipment was assumed to be approximately 4 years old. Use of used equipment reduced system cost per productive hour by 16.5 percent on the average for the four systems tested, assuming identical operating costs for new and used equipment. However, higher maintenance and repair costs, and/or lower machine utilization rates of used equipment could nullify these savings. To assess the effects of higher operating costs upon the economics of using used equipment, operating costs were varied as follows:

- vary maintenance and repair costs
  25 percent higher
  50 percent higher
  100 percent higher

Table 3.--Summarized harvest system cost/cunit per productive hour

System	Product	Stand basal area (Square feet per acre) 40 / Average diameter (Inches) 6"	40 / 10"	80 / 6"	80 / 10"	120 / 6"	120 / 10"	Average cost
Tree length logging/chipping[1/]	Pulpwood chips	68.34	37.12	45.93	33.32	38.74	30.80	42.38
22" WTC/sort[3/]	Chips	53.64	37.47	46.38	31.23	44.01	29.38	40.35
22" WTC	Chips	41.60	28.56	35.63	23.80	33.80	22.39	35.94
Mechanized fell/ manual buck (3)	Pulpwood	62.55	21.24	42.07	17.43	35.48	16.13	32.48
Mechanized tree-length logging	Pulpwood	56.55	31.52	28.04	31.52	32.08	31.52[2/]	36.87
Mechanized fell manual buck (2)	Pulpwood	53.33	25.21	37.06	22.30	35.05	20.63	32.26
18" WTC/sort[3/]	Chips	49.68	34.81	42.95	29.01	40.76	27.29	37.42
18" WTC	Chips	38.03	26.36	32.89	21.97	31.25	20.88	28.56

1/ Volume of pulpwood and chips combined.

2/ System reached estimated maximum production due to equipment restraints.

3/ Sixteen percent of total volume processed through system was saw logs. Cost of chips includes cost of bucking out saw logs.

Table 4.--Harvest system costs per productive hour for new and used equipment

System	System cost per productive hour		
	New	Used	Percent
	- - - Dollars - - -		
Tree-length logging/chipping	455.15	375.88	(-17)
22-inch whole-tree chip/sort	378.79	310.13	(-18)
22-inch whole-tree chip	362.60	293.74	(-19)
18-inch whole-tree chip	228.44	201.11	(-12)

- vary machine utilization rate
  5 percent lower
  10 percent lower
  20 percent lower
- vary a combination of
  25 percent higher maintenance and repair with 5 percent lower utilization
  50 percent higher maintenance and repair with 10 percent lower utilization
  Doubled higher maintenance and repair with 20 percent lower utilization.

Assuming identical operating costs for new and used equipment, all systems with used equipment had significantly lower costs per cunit. The 22-inch whole-tree chip system had the lowest average cost of $22.15 per cunit. As operating costs were increased, used equipment cost per cunit approached that of new equipment. Lower utilization rates had a greater effect on costs than the increased maintenance and repair costs used in this comparison. When utilization rates decreased to 20 percent below new, costs per cunit were higher than for new equipment costs except for the 22-inch WTC system. When maintenance and repair costs were doubled, costs per cunit were still under those of new equipment. A combination of 50 percent higher maintenance and repair costs with 10 percent lower utilization rates resulted in per cunit costs approximately equal to those of new equipment (except for the used 22-inch WTC system which was still $6 under new equipment costs per cunit). Therefore, even with relatively high operating costs, used equipment appears to lower costs per cunit compared to systems utilizing new equipment.

Fuel Harvest Computer Program

Further investigation of the harvest system cost data was facilitated through the use of the Fuel Harvest Analysis (FHA) Computer Program developed by Harpole in 1983. The FHA program uses harvest system costs and converts these costs into dollars per million Btu's as recovered from a boiler. The energy costs are computed as a residual and include all costs and revenues that are incurred by harvesting other non-fuel products. Multiple harvest systems may be compared and the lowest cost producing system identified for each harvest unit considered.

In this analysis, 12 harvest units were considered. Each unit was harvested by each harvest system and each harvest system could produce fuel chips. In this data set, estimated stumpage and transportation costs are included with system costs.

Costs per million Btu's ranged from $2.13 to $0.41 (table 6). The whole-tree chip systems with used equipment were the lowest cost systems if volume per acre was low. With larger volumes per acre, the used-tree-length logging/chipping system was the lowest cost system. Note that the same operating costs for both new and used systems are assumed. Higher operating costs for used equipment would change the results.

It is assumed that the used-tree-length logging/chipping system was the lowest cost system due to its

Table 5.--Summarized harvest system average cost/cunit per productive hour for used equipment varying operating cost variables

System	New equipment	Used equipment identical operating costs	Higher maintenance and repair costs			Lower utilization rates			Combination		
			25 percent	50 percent	Doubled	5 percent	10 percent	20 percent	25/5 percent	50/10 percent	Double/20 percent
Tree-length logging/chipping	42.38	35.00	35.95	36.90	38.81	37.15	39.68	46.27	38.18	41.91	51.63
22" whole-tree chip/sort	40.35	33.04	33.67	34.30	35.56	34.86	36.99	42.48	35.54	38.45	45.97
22" whole-tree chip	35.94	22.15	25.55	26.05	27.06	26.41	28.01	32.13	26.95	29.18	34.93
18" whole-tree chip	28.56	25.11	25.59	26.07	27.38	26.60	28.34	32.88	27.11	29.47	35.60

Table 6.--Summary of fuel harvest program output

Unit number	Harvest unit		Least cost harvest system	Cost/mmBtu
	Basal area	Average d.b.h.		
1	40	6	Used--18" WTC	2.13
2	40	8	Used--18" WTC	1.61
3	40	10	Used--Tree-length logging/chipping	1.60
4	40	12	Used--Tree-length logging/chipping	1.22
5	80	6	Used--22" WTC	1.87
6	80	8	Used--22" WTC	1.40
7	80	10	Used--Tree-length logging/chipping	.73
8	80	12	Used--Tree-length logging/chipping	.89
9	120	6	Used--Tree-length logging/chipping	1.70
10	120	8	Used--Tree-length logging/chipping	.67
11	120	10	Used--Tree-length logging/chipping	.41
12	120	12	Used--Tree-length logging/chipping	.59

multiproduct output. With larger volumes per acre, pulpwood revenue offset fuel chip cost. With low volumes per acre, it appears to be cheaper to produce chips only.

Both "cost per cunit" and "cost per Btu" analyses, identify whole-tree harvesting systems as the lowest cost systems. The FHA program picked the used tree-length logging (pulpwood or saw log)/chipping (fuel chips) system with higher volumes per acre because high value products (pulpwood or saw log) would be produced with the fuel chips. The revenue from these products offsets the fuel chip cost. The mechanized fell/manual buck systems were not considered by the FHA program because fuel chips were not produced.

SUMMARY AND CONCLUSIONS

Production and cost were estimated for eight harvesting systems based on the literature for a range of basal areas and average stand diameters for typical northern Minnesota aspen stands. Machine costs were calculated according to standard methods. Harvest system costs per cunit per productive hour were calculated using both new and used equipment investment costs.

An 18-inch whole-tree chip system was found to yield the lowest average cost per cunit for systems based on new equipment ($28.56). High equipment prices increased system costs for the large mechanized systems. The highest cost per cunit was incurred by a tree-length logging chipping system ($42.38). Adding sorting capabilities to tree-length logging and whole-tree systems added an average of $6.26 to cost per cunit. All system costs varied significantly with changes in either basal area or average d.b.h.

When used equipment costs were substituted for new machine costs, the 22-inch whole-tree chip system had the lowest cost per cunit of four systems studied ($22.15). Used equipment investment costs lowered harvest system equipment costs an average of 40 percent. Operating costs were varied for the used machines to determine the effects of higher operating costs on system cost per cunit. Used equipment yielded lower costs per cunit than comparable new systems even considering 50 percent higher maintenance and repair costs, and a 10 percent lower machine utilization rate. Both new and used system costs were evaluated to determine costs per mmBtu using the Fuel Harvest Computer program. The tree-length logging/chipping system was the lowest cost system. Costs ranged from $2.13 to 0.41 per mmBtu.

Future harvesting research will concentrate on biomass harvesting and small-scale logging problems and opportunities.

FUTURE MARKET UNCERTAINTY: A CASE FOR SHORT-ROTATION SYSTEMS[1]

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Aspen (*Populus tremuloides Michx. and Populus grandidentata* Michx.) has only recently been in great demand in northeastern Minnesota. Although the aspen supply in the region is currently abundant, a shortage could develop because of the imbalanced age distribution of aspen. Today's forest contains many financially mature and overmature aspen stands and few young aspen stands because few stands have been cut, and without cutting, aspen has not regenerated well. High aspen demand coupled with decreases in aspen supply after the currently mature aspen stands are cut could greatly increase aspen prices. However, changes in utilization standards could also shift some aspen demand towards lower value hardwoods and thus tend to keep aspen prices down. The utilization research and development efforts that led to increased aspen demand were stimulated by the relative abundance and low price of aspen. A similar series of events could unfold around the lower value hardwoods if aspen prices increase significantly. That would greatly affect wood energy use because the lower value hardwoods, of all species groups, have the greatest potential for such use. The future aspen supply is thus a critical issue.

INCREASING ASPEN SUPPLIES

Two possible alternatives for increasing aspen supplies are: (1) introducing short-rotation hybrid poplars (*Populus* hybrids) and (2) conducting timber stand improvement work on overmature and unmarketable existing aspen stands.

Hybrid poplar systems have been recently developed that can produce merchantable size material in 10 to 15 years. Economic analyses using current aspen prices for product price indicate that the systems' financial performance appears marginal at best (Rose *et al.* 1981, Lothner *et al.* 1981, Ferguson *et al.* 1981). However, these analyses also indicate that financial performance is extremely sensitive to product price.

Timber stand improvement work on overmature and unmarketable aspen stands simply involves clearing the stand to stimulate natural aspen regeneration. Both the Superior National Forest and the Minnesota Department of Natural Resources are seriously considering implementing this type of work on a large scale in the next 10 years. This alternative is quite expensive, and most management costs occur immediately. Considering the uncertainty of long-range demand fore-

[1] *The study was supported in part by the Oak Ridge National Laboratory, U.S. Department of Energy.*

[2] *The research was done while Dr. Hoganson was a Principal Economist with the U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station, Duluth, Minnesota.*

casts, such regeneration work may be unnecessary. Postponing present regeneration decisions and possibly introducing short-rotation alternatives at some intermediate time might be a more viable alternative. Both the lack of data and the relation of regeneration decisions to other management decisions complicate analyses of regeneration alternatives. We will compare a short-rotation hybrid poplar system with one method of stand clearing to stimulate aspen regeneration. The purpose of the comparison is to examine a potential advantage of short-rotation systems resulting from an uncertain future timber market.

REGENERATION DECISIONS AND UNCERTAINTY

The many authors focusing on uncertainty in forest management agree that much uncertainty exists, it cannot be eliminated, and therefore, it must be recognized in the decisionmaking process. Several authors suggest using quantitative techniques for forestry decisionmaking under risk and emphasize the need to view planning as a continuous process in which revising and updating are the general rule (Marty 1964, Thompson 1968, Thompson 1972, Fight and Bell 1977, and Hassler and Sinclair 1982). The overall goal must be to select flexible management alternatives that will perform well under a wide range of possible outcomes. Carder and Oglesby (1973) state that the need for maintaining flexibility is evident in the language used in national forest guidelines, directives, and regulations. Phrases such as "manage the present to insure the future," "avoid irreversible mistakes," and "keep options open" are quite common. Fight and Bell (1977) indicate that the USDA Forest Service has maintained flexibility by carrying a large inventory. Although a large inventory allows for flexibility in future harvest levels, such a policy is usually expensive. Short-rotation systems might allow forest managers to maintain this flexibility at a much lower cost.

What to plant, how much to plant, where to plant, and when to plant are all important regeneration issues for a forest as a whole. These issues depend heavily on current harvest decisions, resources available, and future market conditions. The uncertainty surrounding future market conditions, specifically future market prices and future consumption levels, makes it difficult to evaluate alternatives. Yet strategies are being formulated and implemented today to produce wood for future periods. Regeneration activities implemented are generally irreversible and have high front-end costs. The uncertainty of future market conditions must be recognized in developing strategies. Unfortunately, the complexity and size of the overall management system make it difficult, if not impossible, to recognize market uncertainty explicitly when examining the system as a whole.

One simple way of examining just the regeneration decision is to view it as a problem in which we are forced to decide today how much wood to produce for a future time under uncertain future timber prices. Figure 1 illustrates the uncertainty surrounding future prices and a potential advantage of short-rotation systems. In year 0 we are at point P, and the two-dimensional "cone" with vertex point P represents all of the possible future real prices. The convex-shaped boundaries of the cone represent the maximum and minimum exponential rates for price changes. At the time of harvest, H, the "cone" could be quite wide. With short-rotation systems we could postpone the regeneration to approximately year ½ H and still produce timber volumes in year H. A "cone" can also be constructed to describe the future price uncertainty when the short-rotation system is implemented. It is illustrated in figure 1 by the "cone" with its vertex at point F. Conceptually

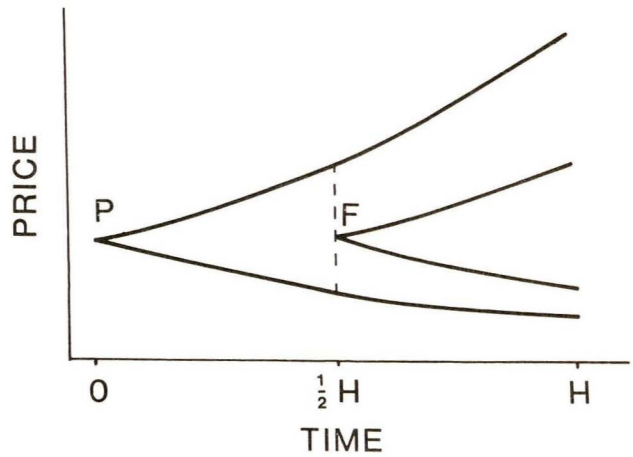

Figure 1.—*The "cones" of price uncertainty for two regeneration alternatives. The "cone" with the vertex at point P represents the range of market prices from the present to period H that sellers might expect if they decide to invest in a conventional management system in period zero. The "cone" with the vertex at point F represents the range of market prices from period ½ H to period H that sellers might expect if they postpone their investment decision until period ½ H and then invest in a short-rotation system. The inner cone is one of a family of identically shaped cones with vertices positioned along the broken line. The difference in width of the two "cones" illustrates the price uncertainty that could possibly be overcome by delaying the regeneration decision until ½ H when prices in period H might be less uncertain.*

Table 1.--The dollar value and timing of expenditures and receipts of two management systems for producing initial yields in year 30 [1/]

Management system	Expenditure and receipt items	Values/acre (Dollars)	Years
Aspen	Land purchase	100.00	0
	Site preparation	135.00	0
	Administration	7.50	0
	Full tree harvest	740.00	30,60
	Product sale (41.0 dry tons X $25.00)[2/]	1,025.00	30,60
	Land sale	100.00	60
Short-rotation poplar	Land purchase	100.00	15
	Site preparation	385.00	15
	Site preparation	35.00	16
	Planting	60.00	16
	Administration	7.50	15,16
	Cultural tending	14.00	17
	Full tree harvest	850.00	30,45
	Product sale (47.25 dry tons X $25.00)	1,181.00	30,45
	Full tree harvest	740.00	60
	Product sale (41.0 dry tons X $25.00)	1,025.00	60
	Land sale	100.00	60

1/ Metric equivalents: 1 acre = 0.405 ha; 1 dry ton = 0.90 metric tons.
2/ For illustration purposes, a $25.00 per dry ton product value was used in this table. In our analyses, we changed price at average annual rates ranging from -1 percent to 3 percent from this $25.00 base price.

Source: Basic data taken from Rose et al. (1981) and information on file with the Superior National Forest (modified by authors to reflect the forestry situation in northern Minnesota).

speaking, the size of the two "cones" illustrates the price uncertainty that could be overcome by delaying production decisions until year ½ H when prices in year H should be less uncertain. The broken line in figure 1 indicates the locus of possible vertices for the inner cone.

COMPARISON OF TWO SYSTEMS

We will compare a short-rotation hybrid system recommended by Hansen *et al.* (1983) to a stand clearing system for stimulating natural aspen regeneration. Table 1 shows the general cash flow information for the two systems. The stand clearing system is being evaluated for implementation by the Superior National Forest (table 1). Cost information for the short-rotation system was obtained from Rose *et al.* (1981), and the system was modified slightly to reflect the forestry situation in northern Minnesota. Specific silvicultural detail of the two systems are incidental to our purpose. We assume that an overriding goal is to produce wood in year 30. The starting times of the two systems are staggered. The aspen system is initiated immediately; the hybrid poplar system is initiated in year 15. In this way, both systems produce their largest discounted return in year 30. Additional rotations for both systems are included to recognize the advantages of an established root stock with both hybrid poplars and aspen. The financial measure to use for comparing systems depends on the situation faced by management. We chose the internal rate of return (IRR) because available capital is the most limiting resource in many cases. The net discounted benefit per unit of timber produced might also be an appropriate measure because the level

of demand is often the limiting factor for a region as a whole. Both IRR and the net discounted benefit per unit of timber produced are relative measures. Results with each would be quite similar. The land values used in the analysis reflect values for use other than timber production, and thus, the fact that the values are equal for both alternatives does not imply that the alternatives involve the same site or even equivalent sites in terms of timber production. We assume that both sites are at equal distances to market only to eliminate any locational effect for the comparison. Land costs are not assumed for the SRIC system until year 15 because land is available, and no commitment is necessary until year 15. A primary advantage of the SRIC system is that decisions on whether or not to implement it can be delayed until year 15 when more information is available concerning future prices as well as other potential systems that might be developed in the mean time.

The financial performance of both systems is very sensitive to timber prices. Assuming that the current $25 per dry ton market price remains stable, neither system appears to be a wise investment because both earn rates of return less than 4 percent, the alternative rate of return used by the Forest Service (Row *et al.* 1981). However, increasing timber prices relative to other management expenditures have a dramatic positive impact on the IRR for both systems.

Predicting future prices is extremely difficult. We assume a probability distribution on future prices to illustrate a point about uncertainty. Before a definite decision can be drawn about the overall value of either system, a more thorough analysis would be needed to examine the sensitivity of results to the distribution assumed, other sources of uncertainty, and other related management issues. We assume that the average annual real price increase for the next 30 years can be described by a triangular distribution with a most likely price increase of 1 percent, a maximum price increase of 3 percent, and a minimum of – 1 percent. After year 30, we assume real prices will remain constant. Using $25 as today's price, we translate this into real prices ranging from $18.50 to more than $60 per dry ton in year 30. Although this might appear to be a wide range, timber prices for other species are already significantly above $60 per dry ton. Our "cone of uncertainty" surrounding future timber prices is shown in figure 2.

With the aspen system, actions must begin today to produce wood for year 30. Much risk is involved because of the large cost (commitment) initially involved. Given the probability distribution for price changes and the price at the time of the initial investment, we can estimate the probability distribution for the financial performance measures. Figure 3A shows the uncertainty surrounding IRR for the aspen investment. If 4 percent is the alternative rate of return, then a decision on

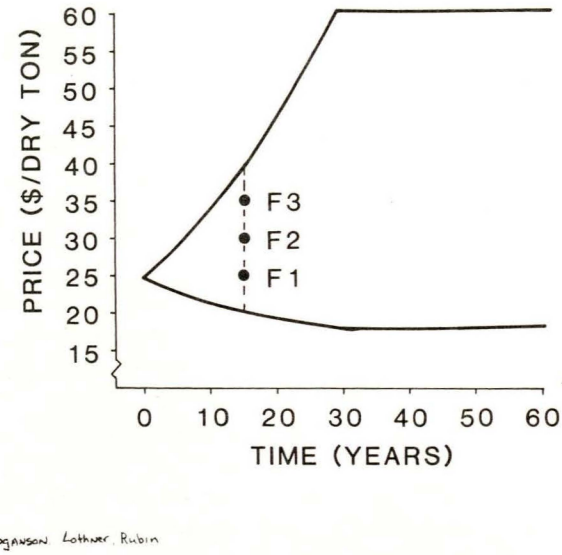

Figure 2.—*The "cone" of price uncertainty stemming from a present-day price and future price assumptions. The "cone" is described by a triangular distribution with a most likely annual price increase of 1 percent, a maximum annual price increase of 3 percent, and a minimum of – 1 percent. The broken line represents the locus of possible prices in year 15. Points F1, F2, and F3 on the line represent annual price increases of 0, 1, and 2 percent, respectively.*

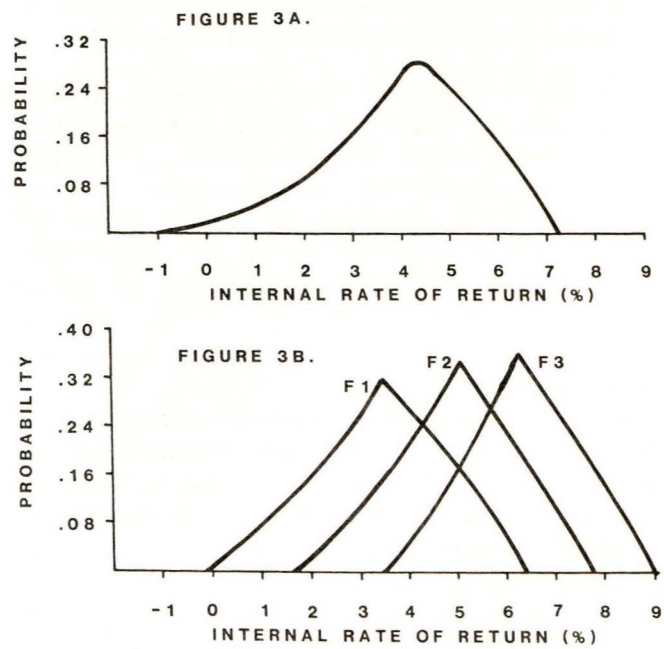

Figure 3.—*The probability distribution of the IRR for: (A) a natural regeneration system and (B) a short-rotation hybrid system. Each IRR distribution is derived assuming a triangular probability distribution of real annual average price increases with a most likely price increase of 1 percent. In figure 3B a probability distribution is shown for each of three plausible prices (F1, F2, and F3, see figure 2) for year 15, the year of critical investment.*

whether to undertake the traditional alternative would be difficult. Rates of return range from – 1 percent to 7.25 percent with a mean very close to 4 percent.

With the short-rotation hybrid system, decisions can be delayed until year 15 and yet wood can still be produced in year 30. Based on our assumption describing real price increases, a new cone will be formed in year 15 with its vertex at the year-15 price. This price will not become known until year 15. For our comparison we considered three plausible prices for year 15—$25, $29, and $33.50. These prices represent 0-percent, 1-percent, and 2-percent average annual increases over the first 15 years. For each of these plausible year-15 situations (points F1, F2, and F3 in figure 2), probability distributions were calculated for the IRR from investing in the short-rotation hybrid system in year 15. These calculations used the same price increase assumptions that were used to calculate the IRR probability distribution for the aspen system. Figure 3B shows the distributions on IRR for the 3 year-15 prices considered. The distributions are narrower than for the aspen system. Also, these distributions do not all center near the 4-percent alternative rate of return. For point F3, the obvious decision would be to invest; the downside risk is minimal because there is very little risk of a return of less than 4 percent. For points F1 and F2, the choice is not as obvious, but most decisionmakers who use an alternative rate of return of 4 percent would probably invest at point F2 and not invest at F1.

To examine the ability of delaying decisions until year 15, we used probabilities for F1, F2, and F3 occurring and developed a single IRR distribution for the SRIC alternative. Probabilities were derived by dividing the triangular distribution on the price trend for the first 15 years into three discrete regions so that the region means corresponded with the price increases assumed for cases F1, F2, and F3. The break points in the triangular distribution were price increases of ½ percent and 1½ percent. The probabilities of F1, F2, and F3 were calculated as 0.28125, 0.4375, and 0.28125, respectively. With F1 occurring, it was assumed that the 4-percent alternative rate of return would be selected; the SRIC alternative was selected for outcomes F2 and F3. The resulting distribution is shown in figure 4. The distribution represents the probabilities of SRIC outcomes as viewed in year 0. It is only an approximation of the actual distribution because means of the discrete regions of the price trend distribution were used in deriving it. A Monte Carlo simulation method could be used to derive better estimates, but considering the lack of precision surrounding the estimates of future price trends, there is little need for a more precise estimate of the IRR distribution. The real significance of the distribution shown in figure 4 is the relatively low probability of a return less than the assumed 4-percent

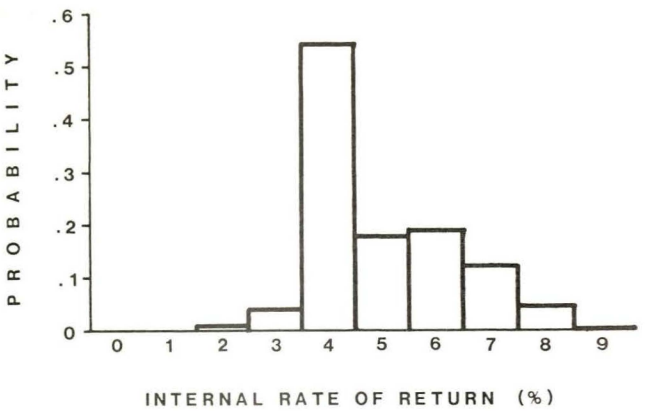

Figure 4.—*The probability distribution of the IRR for the short-rotation alternative. The distribution is only an approximation. It was derived by considering the three cases shown in figure 3B. For the lowest level price, the decision is to invest at the 4-percent alternative rate; the SRIC alternative was chosen for the other two cases.*

alternative rate of return. The ability to delay decisions thus reduces downside risks.

DISCUSSION

Although we looked at specific investment costs and returns in our comparison, it is not difficult to generalize somewhat. Applying the same SRIC system on a more expensive site would be a good example. For this case, the net impact would shift the IRR distributions of figure 3B to the left, and this shift might cause the decision in year 15 to be invest only if outcome F3 occurs. The major impact on the IRR distribution shown in figure 4 would be an increase in the probability of a 4 percent return (no investment) and a decrease in the probability of higher returns. The downside risk would not be affected significantly.

We assumed that future prices are independent of the regeneration decision. Obviously, for large landowners they are not. Demands for timber products are very inelastic. Therefore, changes in the general market supply (regeneration level) can significantly influence market price, but influence the consumption level very little. From the public's viewpoint, this means that it is expensive to carry a surplus inventory to overcome uncertain future demands; additional regeneration work results in only a small increase in the consumption levels. Intuitively we might think that any surplus inventory in one period could be used in the next period. To a certain extent this is true, but we must also remember that regeneration work has already been completed to produce supplies for periods far into the future. In other words, once a large inventory develops, it is not easily reduced because of the time lag involved

within the total forest management system. A partial reliance on shorter rotation species might lead to much greater flexibility.

The uncertainty surrounding future timber prices makes it extremely difficult to evaluate specific management alternatives on specific sites. Definite answers are seldom possible. A recent trend in the Forest Service is to take a much more systematic approach by considering all stands in an entire forest together by using a large linear programming model. These models are very useful in that they can help put the management of specific stands into perspective with the management of other stands and the goals for the forest. One major shortfall of these planning models is their inability to recognize the uncertainties surrounding model inputs, including price uncertainty. By ignoring uncertainty, the large-scale planning models are not recognizing the differences in flexibility between different model alternatives. Consequently, models of this type are not appropriate for evaluating the full potential of short-rotation alternatives. The complexity of forest management decisions makes it impossible to obtain a complete picture from a single model. Decisionmakers must recognize the limitations of each quantitive technique they use. A real challenge they face is to synthesize the results from available models and add their own judgment about concerns not adequately described in the modeling process.

In our example, we ignored uncertainties surrounding variables other than price used in our cash flow analyses (table 1). Simulation approaches like those proposed by Hertz (1964) might be more appropriate for examining the current state of uncertainty surrounding specific alternatives. We would expect that distributions surrounding returns are wider when all types of uncertainty are considered. But let's not forget that some of this uncertainty could be overcome through research and experience. The short-rotation system used in our example already exists. If regeneration can be delayed for 15 years, as in our example, perhaps even better systems can be developed before implementation is necessary.

CONCLUSIONS

When future timber demand levels or future timber prices are uncertain, short-rotation systems can allow forest managers to delay or postpone some investment decisions. As more information becomes available on future market conditions, it can be used to evaluate the need for additional investments. This approach reduces the likelihood of making unprofitable or unnecessary investments.

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ESTIMATING WOOD ENERGY DEMAND IN NORTHEASTERN MINNESOTA

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Estimates of potential wood energy demand in northeastern Minnesota were needed for two purposes: First, the timber supply study by Hoganson required wood energy demand estimates to add to the demand projections for other forest products; second, Lichty *et al.* needed estimates of the size of a potential wood energy industry to measure regional economic impacts.

Estimating wood energy demand required three steps. First, using a 1977 input/output model of the study region we estimated the volume and cost of existing fossil fuel use for 31 key energy-using sectors. Second, we calculated the green tons of wood fuel required (as well as any cost savings generated) to replace a unit of coal, oil, or natural gas. Using a spreadsheet, we related (1) BTU content, (2) combustion efficiency, and (3) price of coal, oil, gas, dry wood pellets, green chips, and air-dry roundwood to determine the volume and costs of green wood required to replace a unit of any fossil fuel. Third, we used a second spreadsheet to combine current fossil energy use, wood conversion scenarios, and the wood volume and costs needed to replace each unit of fossil fuel scheduled for conversion. The result of this third step, when summed over all sectors, shows the total wood volumes and costs of replacing fossil fuels. These data were then conveyed to Hoganson and Lichty for their purposes.

CURRENT FOSSIL FUEL CONSUMPTION (1977)

Using a 1977 input/output model of the northeastern Minnesota economy, coal, petroleum, and natural gas purchases were examined. Of 223 sectors, 31 used 97 percent, 89 percent, and 95 percent of all coal, oil, and natural gas purchased in the region. These 31 sectors form the basis for estimating future wood energy demand scenarios.

Using fuel price data by sector grouping (table 1), we then converted these fossil fuel purchases into physical volumes and BTU contents (table 2).

Table 1.--Assumed fuel prices by sector group, 1977

(In dollars per million Btu's as fired)

Fuel	Sector group				
	Housing	Commercial	Industrial	Transport	Utility
Coal	3.0100	0.9540	0.9540	0.9540	0.6946
Fuel oil	3.1957	2.9375	2.7571	3.2893	2.6292
Natural gas	2.1384	1.7189	1.1263	1.2396	1.0946
Wood pellets	2.1875	2.1875	2.1875	2.1875	2.1875
Wood chips	.8865	.8865	.8865	.8865	.8865
Roundwood	.9259	.9259	.9259	.9259	.9259

Table 2.--Base-line fossil fuel consumption in 1977 by volume and energy content

Sector	Volume			Energy content			
	Coal (Tons)	Fuel oil (Thousand gallons)	Natural gas (Million cubic feet)	Coal	Fuel oil	Natural gas	Total Btu's
				(Million Btu's)			
Iron mining	186,452	54,563	16,580	4,685,535	7,638,823	16,579,952	28,904,310
Highway construction	0	5,736	1	0	803,018	888	803,906
Well drilling	0	30,042	0	0	4,205,868	0	4,205,868
Maintenance	83	6,998	7	2,096	979,653	7,103	988,852
Meat products	1,543	811	174	38,784	113,525	174,021	326,330
Milk products	1,668	1,728	107	41,929	241,921	107,431	391,281
Frozen fruit and vegetables	0	1,826	258	0	255,703	258,368	514,072
Logging and sawmill	17,853	14,376	24	448,637	2,012,622	23,972	2,485,232
Pulp and paper	202,427	34,954	4,072	5,087,002	4,893,548	4,071,739	14,052,289
Chemicals 1	4,839	1,816	287	121,593	254,253	286,780	662,626
Chemicals 2	751	2,876	1,236	18,868	402,597	1,235,905	1,657,370
Chemicals 3	1,585	2,262	58	39,832	316,637	57,711	414,180
Petroleum refining	8,718	57,480	1,823	219,078	8,047,224	1,822,783	10,089,084
Asphalt and pavement	3,003	9,788	70	75,472	1,370,280	70,141	1,515,893
Miscellaneous stone	2,294	1,946	465	57,652	272,388	465,240	795,280
Blast furnaces	77,584	1,402	522	1,949,686	196,221	522,063	2,667,970
Railroads	0	14,480	178	0	2,027,179	178,283	2,205,462
Trucking	0	2,906	5	0	406,773	4,840	411,614
Water shipping	83	2,547	9	2,096	356,611	8,874	367,581
Electric utility	984,973	36,323	4,868	24,752,375	5,085,197	4,867,532	34,705,104
Gas utility	0	182	19,933	0	25,483	19,933,309	19,958,792
Wholesale trade	250	8,117	73	6,289	1,136,340	72,721	1,215,351
Retail trade	1,043	9,116	419	26,205	1,276,255	419,454	1,721,915
Real estate	0	5,452	194	0	763,234	193,729	956,963
Hotels	0	1,656	130	0	231,830	130,316	362,146
Restaurants	0	163	87	0	22,809	87,265	110,074
Health services	1,752	3,589	182	44,025	502,468	181,511	728,005
Government enterprise	29,407	3,052	568	738,994	427,234	568,387	1,734,615
Households	5,513	87,805	6,611	138,538	12,292,768	6,610,550	19,041,857
Federal government	4,088	6,125	119	102,725	857,532	118,681	1,078,938
State and local government	5,464	14,750	2,023	137,317	2,065,021	2,022,805	4,225,143
Total	1,541,374	424,864	61,082	38,734,729	59,481,015	61,082,355	159,298,099

WOOD CONVERSION SCENARIOS

To develop future fuel use scenarios, we estimated the amount of fossil fuels that might be displaced by wood. While the ultimate causes for the displacement are unknown, they will probably result from a combination of factors, such as fuel price differences, government tax policies, and perceived fossil fuel shortages.

As one might expect, different energy users face different problems and opportunities when converting to wood fuels. For each sector, we first tried to define the maximum opportunity for substituting wood fuels for fossil fuels. Once this maximum level was established, we then developed two more likely possibilities which were then followed through the analyses.

There are two major categories of users in the input/output model: (1) industries and businesses that make, distribute, or service all of the products the economy needs; and (2) so-called "final demand" users, consisting of households, government, and exports that absorb the final outputs of industries and businesses.

The industrial portion of the input/output model is divided into about 200 sectors. But if we include only those sectors purchasing more than $1,000,000 of energy (1977 prices), the resulting 28 sectors account for over 90 percent of all energy use. Thus, only the fossil fuel demands of these 28 industrial sectors were used in developing the two wood energy displacement scenarios.

The final demand portion of the input/output model was divided into households, State and local government, and Federal government, bringing the total number of energy-using sectors to 31.

INDUSTRIAL USE

Coal

Cost and convenience aside, there is probably no technical reason why most coal use could not be entirely displaced by wood. The blast furnace sector, which uses coal to produce coke for the smelting process, is an exception. All other coal use, including that of electric utilities, could be replaced by wood.

Natural Gas

Like coal users, most natural gas users could substitute wood. The primary exceptions are the iron mining, pulp and paper, and blast furnace sectors, which burn large quantities of natural gas to dry taconite pellets, dry paper, or smelt ore. We assumed that no more than 20 percent of the natural gas consumption for these sectors could be replaced by wood. (This assumption has recently been proved wrong; a major taconite pelletizer has installed a wood burning system with apparent success.)

Other exceptions include the chemicals, petroleum refining, and gas utility sectors, which use natural gas both as process energy and as feed stock. It seems highly unlikely that these industries will reduce consumption of a fuel that they themselves produce and that is, in fact, their main raw material or a very close adjunct. For these sectors, we assumed that no natural gas consumption would be replaced by wood.

We assumed that all remaining industries could convert no more than 80 percent of their natural gas consumption to wood. The balance would be consumed in nonseasonal uses such as water heating, where it would be difficult for wood to displace natural gas.

Petroleum (Fuel Oil)

Estimating the potential for petroleum replacement by wood is complicated by the fact that available data do not permit a precise division of petroleum use into space heat, process heat, and transportation. While it was possible to estimate the ratio of space and process heat to total petroleum use for *all* industries, we were forced to make crude estimates for specific industries.

Petroleum use by the iron mining sector in northeastern Minnesota is predominantly for diesel-powered trucks and trains. Thus, we assumed that only 10 percent of its petroleum use could be replaced by wood. The construction, logging, miscellaneous stone, transport, and wholesale trade sectors were treated similarly.

On the other hand, many sectors (food processing, retail trade, real estate, lodging, restaurants, hospitals, State and local enterprise) have a relatively small transportation segment, and we assumed that these sectors could replace up to 75 percent of their petroleum consumption with wood. Seventy-five percent is approximately the statewide average fuel oil heating proportion of total petroleum consumption by the commercial sector.

Two other major industries consuming large quantities of petroleum—pulp and paper and electric utilities—have an even smaller transport use. Thus, we assumed that these two sectors could convert up to 90 percent of their fuel oil use to wood.

The remaining sectors, petroleum refining, paving and asphalt, blast furnaces, and gas utilities, were assumed to make no petroleum conversion to wood fuels, either because they need high-quality energy sources for their processes, or because they are so closely associated with the petroleum industry that conversion is unlikely. (Here, too, the assumption that paving and asphalt users will not use wood or other nonpetroleum fuels has recently been proven wrong.)

FINAL DEMAND USE

Coal

We assumed that the household, State and local government, and Federal government sectors could convert 100 percent of their coal consumption to wood.

Natural Gas

While we assumed that the gas utility sector would convert none of its inputs to wood (although it is conceivable that wood can be gasified and marketed through normal pipelines), the final demand sectors could convert some of their gas use to wood. We assumed that only that portion of gas used for space heating would convert—that is, the seasonal gas use to heat homes, not the year-round use to heat water or dry clothes. Based on data from the Duluth Water and Gas Department, we assumed that this limit was 75 percent for all residential gas consumption and 80 percent for governmental gas consumption.

Petroleum (Fuel Oil)

Here, too, we had difficulty estimating the space heat and transport components of petroleum use. Based on national statistics and some simple ratios, we estimated that Minnesota households use about 55 percent of their total petroleum consumption for home heating. The balance is for transportation and other uses.

For the government sectors, we assumed that petroleum use parallels the commercial sectors already mentioned. Thus, no more than 75 percent of government fuel oil use can be replaced by wood.

Table 3 shows the upper limit on wood fuel conversions by fuel type (coal, fuel oil, natural gas) and by sector. The limits are expressed as a percent of 1977 fossil fuel use.

Given these maximum "possible" levels, we then developed two wood conversion scenarios to be used by both Hoganson and Lichty. Instead of trying to predict how *each* sector might switch, we grouped sectors by (1) the level of certainty surrounding our guess and (2) the predicted rate of conversion to wood.

Table 3.--Maximum wood fuel substitution rates by fossil fuel and sector

(In percent)

Sector	Coal	Fuel oil	Natural gas
Iron mining	100	10	20
Construction	100	10	80
Food processing	100	75	80
Logging and sawmill	100	10	80
Pulp and paper	100	90	20
Chemicals	100	0	0
Petroleum refining	100	0	0
Asphalt and pavement	100	0	80
Miscellaneous stone	100	10	80
Blast furnaces	0	0	20
Transport	100	10	80
Electric utility	100	90	80
Gas utility	100	0	0
Wholesale trade	100	10	80
Retail trade	100	75	80
Real estate	100	75	80
Hotels	100	75	80
Restaurants	100	75	80
Health services	100	75	80
Government enterprise	100	75	80
Households	100	55	75
Federal government	100	75	80
State and local government	100	75	80

Sector group	Level of certainty	Rate of conversion to wood
1. Forest industries and public sectors	High	High
2. Households	High	Low; conversions already extensive
3. Petroleum and gas utilities	High	None
4. Manufacturing and commercial sectors	Low	Moderate
5. Electric utilities and iron mining	Low	Two conversion levels were assumed: 15 percent 25 percent

It is highly likely that both the public and the forest industry sectors will make significant wood conversions by the year 2000, because of the political and economic sense it makes. Households in northeastern Minnesota have already achieved a 25 to 30 percent conversion and will continue to convert if fossil fuel costs continue to rise and wood becomes more convenient to burn. However, the rate of conversion probably will slow. The petroleum, gas utility, and related sectors will make almost no use of wood or other biomass fuels for obvious reasons. Commercial and industrial sectors (excluding iron mining) face an uncertain conversion future. While there are now and will continue to be economic incentives for them to use more wood fuels, many factors make guessing difficult. However, because their combined impact is small relative to the others, it makes little difference what level we assume.

The two sectors that could have the greatest impact—electric utilities and iron mining—also have the most uncertain rates of conversion from coal to wood for producing electricity. These two sectors dominate our scenarios; for example, in Scenario 1 we assumed a 15 percent conversion of coal use to wood, and in Scenario 2 we assumed a 25 percent conversion (table 4).

WOOD FUEL REQUIREMENTS PER UNIT OF FOSSIL FUEL REPLACED

Determining the quantity and cost of wood to replace any fossil fuel requires several kinds of data: (1) energy content, (2) combustion efficiency, (3) wood fuel preference, and (4) prices. The first two, energy content and combustion efficiency, interact to determine the amount of usable energy produced by the burner. Both vary widely even within the same fuel type and within the same kind of furnace. Table 5 shows the values assumed in this study.

The usable burner output is the appropriate benchmark for comparing different fuels, for it is at this point that a user must compare costs. Burner output is simply the product of unit energy content and combustion efficiency. An extra calculation for wood fuels was required, however. Because one of our objectives was to calculate the impact of wood fuel use on forests, we needed to know the green tons of wood required to produce a unit of wood fuel, as burned. For roundwood this ratio is 1 to 1. But because varying degrees of drying occur when wood is chipped or pelletized, the tons of green wood input vary.

Next, we assumed different users would prefer their wood fuels in different forms: green roundwood, slightly drier green wood chips, or very dry wood pellets. Table 6 shows these wood fuel preferences by sector group.

Finally, the data in tables 1, 5, and 6 were combined to produce tables 7, 8, and 9 to be used in the final spreadsheet: table 7 shows the *tons of green wood required per unit of fossil fuel* by fossil fuel and sector group. Table 8 shows the *fuel costs per million Btu* by fuel and sector group. Table 9 shows the *dollars of wood fuel required to replace a dollar of fossil fuel* by fossil fuel and sector group.

WOOD REQUIREMENTS AND COSTS, FOSSIL FUEL BALANCE

We can now calculate the green wood tonnage and cost required as well as the fossil fuel balance and any fuel cost savings if the two wood energy demand scenarios shown in table 4 are achieved. Tables 10 through 13 show the results of Scenario 1. Tables 14 through 17 show the results of Scenario 2. Costs assume 1977 prices.

Achieving either scenario would reduce overall coal consumption by 28 or 35 percent, oil consumption by 23 or 24 percent, and natural gas consumption by 16 or 17 percent. In turn, annual wood requirements would increase 4.3 or 4.7 million green tons. This volume is about 38 percent of the current wood consumption for all purposes in the entire State.

At 1977 prices, these wood volumes would cost $46 or $51 million. In contrast, total fossil fuel costs would decline to $218 or $215 million, cuts of $61 or $65 million—about 22 percent. Thus, net fuel cost savings in the region under these two scenarios would be roughly $15 or $14 million—about 5 percent of total regional fuel costs at 1977 prices. Net fuel cost savings decline with the larger fossil-fuel conversions of Scenario 2 because the largest conversions are coal to wood and coal currently costs less than wood.

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Table 4.--Assumed fossil fuel to wood conversion scenarios

(In percent)

Sector	Coal		Fuel oil		Natural gas	
	Scenario		Scenario		Scenario	
	1	2	1	2	1	2
Iron mining	15	25	5		10	
Highway construction	50		5		40	
Well drilling	50		5		40	
Maintenance	50		5		40	
Meat products	50		35		40	
Milk products	50		35		40	
Frozen fruit and vegetables	50		35		40	
Logging and sawmill	80		10		40	
Pulp and paper	80		80		10	
Chemicals 1	25		0		0	
Chemicals 2	25		0		0	
Chemicals 3	25		0		0	
Petroleum refining	25		0		0	
Asphalt and pavement	25		0		0	
Miscellaneous stone	25		10		40	
Blast furnaces	0		0		10	
Railroads	50		5		40	
Trucking	50		5		40	
Water shipping	50		5		40	
Electric utility	15	25	14	20	12	20
Gas utility	50		0		0	
Wholesale trade	50		5		40	
Retail trade	50		35		40	
Real estate	50		35		40	
Hotels	90		35		40	
Restaurants	90		65		70	
Health services	90		65		70	
Government enterprise	90		65		70	
Households	50		35		35	
Federal government	90		65		70	
State and local government	90		65		70	

Table 5.--Assumed combustion efficiency and energy content by fuel

Fuel	Unit	Combustion efficiency	Btu content as purchased	Useable burner output
		(Percent)	- -(Million Btu's per unit)- -	
Coal	Ton	0.7800	25.1300	19.6014
Fuel oil	Thousand gallons	.8000	140.0000	112.0000
Natural gas	Million cubic feet	.8000	1,000.0000	800.0000
Wood pellets	Green ton input	.7800	8.6486	6.7459
Wood chips	Green ton input	.6500	9.4000	6.1100
Roundwood	Green ton input	.4500	9.0000	4.0500

Table 6.--Assumed wood fuel preferences by sector group

(In percent)

Wood fuel	Sector group				
	Housing	Commercial	Industrial	Transport	Utility
Wood pellets	0.2500	0.7500	0.2500	0.7500	0.2500
Wood chips	.0000	.2500	.7500	.2500	.7500
Roundwood	.7500	.0000	.0000	.0000	.0000

Table 7.--Calculated wood requirements per unit of fossil fuel by sector group

(In green tons of wood per fossil fuel unit)

Fossil fuel	Sector group				
	Housing	Commercial	Industrial	Transport	Utility
Coal	4.3563	2.9813	3.1325	2.9813	3.1325
Fuel oil	24.8914	17.0346	17.8986	17.0346	17.8986
Natural gas	177.7958	121.6760	127.8473	121.6760	127.8473

Table 8.--Calculated comparable fuel costs per million Btu's

(In dollars per million Btu's)

Fuel	Sector group				
	Housing	Commercial	Industrial	Transport	Utility
Coal	3.8590	1.2231	1.2231	1.2231	0.8905
Fuel oil	3.9946	3.6719	3.4464	4.1116	3.2865
Natural gas	2.6730	2.1486	1.4079	1.5495	1.3683
Wood pellets	2.8045	2.8045	2.8045	2.8045	2.8045
Wood chips	1.3638	1.3638	1.3638	1.3638	1.3638
Roundwood	2.0576	2.0576	2.0576	2.0576	2.0576

Table 9.--Calculated wood cost to replace a unit of fossil fuel by sector group

(In dollars of wood per unit of fossil fuel)

Fossil fuel	Sector group				
	Housing	Commercial	Industrial	Transport	Utility
Coal	0.5712	1.8140	1.2794	1.8140	1.7572
Fuel oil	.5518	.6042	.4540	.5396	.4761
Natural gas	.8247	1.0326	1.1115	1.4318	1.1437

Table 10.--Scenario 1: calculated green wood requirements by fossil fuel and sector

(In green tons)

Sector	Green tons of wood to replace: Coal	Fuel oil	Natural gas	Total
Iron mining	87,609	48,830	211,970	348,409
Highway construction	0	5,133	45	5,179
Well drilling	0	26,885	0	26,885
Maintenance	131	6,262	363	6,756
Meat products	2,417	5,080	8,899	16,396
Milk products	2,613	10,825	5,494	18,932
Frozen fruit and vegetables	0	11,442	13,213	24,655
Logging and sawmill	44,739	25,731	1,226	71,695
Pulp and paper	507,280	500,501	52,056	1,059,838
Chemicals 1	3,789	0	0	3,789
Chemicals 2	588	0	0	588
Chemicals 3	1,241	0	0	1,241
Petroleum refining	6,827	0	0	6,827
Asphalt and pavement	2,352	0	3,587	5,939
Miscellaneous stone	1,797	3,482	23,792	29,071
Blast furnaces	0	0	6,674	6,674
Railroads	0	12,333	8,677	21,010
Trucking	0	2,475	236	2,710
Water shipping	124	2,170	432	2,726
Electric utility	462,812	91,018	74,676	628,506
Gas utility	0	0	0	0
Wholesale trade	373	6,913	3,539	10,826
Retail trade	1,554	54,351	20,415	76,321
Real estate	0	32,504	9,429	41,932
Hotels	0	9,873	6,343	16,215
Restaurants	0	971	4,247	5,219
Health services	4,701	39,740	15,460	59,900
Government enterprise	78,903	33,790	48,411	161,104
Households	12,008	764,961	411,365	1,188,333
Federal government	10,968	67,822	10,108	88,898
State and local government	14,661	163,321	172,289	350,272
Total	1,247,487	1,926,413	1,112,947	4,286,847

Table 11.--Scenario 1: calculated wood cost by fossil fuel and sector

(In thousand dollars)

Sector	Wood costs to replace: Coal	Fuel oil	Natural gas	Total
Iron mining	858	478	2,076	3,412
Highway construction	0	50	0	51
Well drilling	0	263	0	263
Maintenance	1	61	4	66
Meat products	24	50	87	161
Milk products	26	106	54	185
Frozen fruit and vegetables	0	112	129	241
Logging and sawmill	438	252	12	702
Pulp and paper	4,967	4,901	510	10,378
Chemicals 1	37	0	0	37
Chemicals 2	6	0	0	6
Chemicals 3	12	0	0	12
Petroleum refining	67	0	0	67
Asphalt and pavement	23	0	35	58
Miscellaneous stone	18	34	233	285
Blast furnaces	0	0	65	65
Railroads	0	180	127	306
Trucking	0	36	3	40
Water shipping	2	32	6	40
Electric utility	4,532	891	731	6,154
Gas utility	0	0	0	0
Wholesale trade	5	101	52	158
Retail trade	23	793	298	1,113
Real estate	0	474	138	612
Hotels	0	144	93	237
Restaurants	0	14	62	76
Health services	69	580	226	874
Government enterprise	1,151	493	706	2,350
Households	119	7,587	4,080	11,786
Federal government	160	989	147	1,297
State and local government	214	2,382	2,513	5,109
Total	12,750	21,004	12,386	46,140

Table 12.--Scenario 1: calculated fossil fuel balance by fossil fuel and sector

(In thousand dollars)

Sector	Fossil fuel balance			
	Coal	Fuel oil	Natural gas	Total
Iron mining	3,800	20,008	16,807	40,614
Highway construction	0	2,103	1	2,104
Well drilling	0	11,016	0	11,016
Maintenance	1	2,566	5	2,572
Meat products	19	203	118	340
Milk products	20	434	73	526
Frozen fruit and vegetables	0	458	175	633
Logging and sawmill	86	4,994	16	5,096
Pulp and paper	971	2,698	4,127	7,796
Chemicals 1	87	701	323	1,111
Chemicals 2	14	1,110	1,392	2,516
Chemicals 3	29	873	65	967
Petroleum refining	157	22,187	2,053	24,397
Asphalt and pavement	54	3,778	47	3,879
Miscellaneous stone	41	676	314	1,032
Blast furnaces	1,860	541	529	2,930
Railroads	0	6,335	133	6,467
Trucking	0	1,271	4	1,275
Water shipping	1	1,114	7	1,122
Electric utility	14,614	11,498	4,689	30,801
Gas utility	0	67	21,819	21,886
Wholesale trade	3	3,171	75	3,249
Retail trade	13	2,437	433	2,882
Real estate	0	1,457	200	1,657
Hotels	0	443	134	577
Restaurants	0	44	90	134
Health services	4	517	94	614
Government enterprise	71	439	293	803
Households	209	25,535	9,188	34,932
Federal government	10	882	61	953
State and local government	13	2,123	1,043	3,179
Total	22,073	131,679	64,306	218,058

Table 13.--Scenario 1: calculated fuel cost savings or (loss) by fossil fuel and sector

(In thousand dollars)

Sector	Fuel cost savings or (loss)			
	Coal	Fuel oil	Natural gas	Total
Iron mining	(187)	575	(208)	179
Highway construction	0	60	(0)	60
Well drilling	0	317	0	317
Maintenance	(0)	74	(0)	73
Meat products	(5)	60	(9)	46
Milk products	(6)	127	(5)	116
Frozen fruit and vegetables	0	135	(13)	122
Logging and sawmill	(96)	303	(1)	206
Pulp and paper	(1,085)	5,893	(51)	4,757
Chemicals 1	(8)	0	0	(8)
Chemicals 2	(1)	0	0	(1)
Chemicals 3	(3)	0	0	(3)
Petroleum refining	(15)	0	0	(15)
Asphalt and pavement	(5)	0	(4)	(9)
Miscellaneous stone	(4)	41	(23)	14
Blast furnaces	0	0	(7)	(7)
Railroads	0	153	(38)	115
Trucking	0	31	(1)	30
Water shipping	(1)	27	(2)	24
Electric utility	(1,953)	981	(92)	(1,064)
Gas utility	0	0	0	0
Wholesale trade	(2)	66	(2)	62
Retail trade	(10)	519	(9)	500
Real estate	0	311	(4)	306
Hotels	0	94	(3)	91
Restaurants	0	9	(2)	7
Health services	(31)	380	(7)	342
Government enterprise	(516)	323	(22)	(216)
Households	89	6,162	867	7,119
Federal government	(72)	648	(5)	572
State and local government	(96)	1,561	(79)	1,385
Total	(4,006)	18,849	280	15,123

Table 14.--Scenario 2: calculated green wood requirements by fossil fuel and sector

(In green tons)

Sector	Green tons of wood to replace: Coal	Fuel oil	Natural gas	Total
Iron mining	146,014	48,830	211,970	406,815
Highway construction	0	5,133	45	5,179
Well drilling	0	26,885	0	26,885
Maintenance	131	6,262	363	6,756
Meat products	2,417	5,080	8,899	16,396
Milk products	2,613	10,825	5,494	18,932
Frozen fruit and vegetables	0	11,442	13,213	24,655
Logging and sawmill	44,739	25,731	1,226	71,695
Pulp and paper	507,280	500,501	52,056	1,059,838
Chemicals 1	3,789	0	0	3,789
Chemicals 2	588	0	0	588
Chemicals 3	1,241	0	0	1,241
Petroleum refining	6,827	0	0	6,827
Asphalt and pavement	2,352	0	3,587	5,939
Miscellaneous stone	1,797	3,482	23,792	29,071
Blast furnaces	0	0	6,674	6,674
Railroads	0	12,333	8,677	21,010
Trucking	0	2,475	236	2,710
Water shipping	124	2,170	432	2,726
Electric utility	771,353	130,026	124,460	1,025,839
Gas utility	0	0	0	0
Wholesale trade	373	6,913	3,539	10,826
Retail trade	1,554	54,351	20,415	76,321
Real estate	0	32,504	9,429	41,932
Hotels	0	9,873	6,343	16,215
Restaurants	0	971	4,247	5,219
Health services	4,701	39,740	15,460	59,900
Government enterprise	78,903	33,790	48,411	161,104
Households	12,008	764,961	411,365	1,188,333
Federal government	10,968	67,822	10,108	88,898
State and local government	14,661	163,321	172,289	350,272
Total	1,614,434	1,965,421	1,162,731	4,742,585

Table 15.--Scenario 2: calculated wood cost by fossil fuel and sector

(In thousand dollars)

Sector	Wood costs to replace: Coal	Fuel oil	Natural gas	Total
Iron mining	1,430	478	2,076	3,983
Highway construction	0	50	0	51
Well drilling	0	263	0	263
Maintenance	1	61	4	66
Meat products	24	50	87	161
Milk products	26	106	54	185
Frozen fruit and vegetables	0	112	129	241
Logging and sawmill	438	252	12	702
Pulp and paper	4,967	4,901	510	10,378
Chemicals 1	37	0	0	37
Chemicals 2	6	0	0	6
Chemicals 3	12	0	0	12
Petroleum refining	67	0	0	67
Asphalt and pavement	23	0	35	58
Miscellaneous stone	18	34	233	285
Blast furnaces	0	0	65	65
Railroads	0	180	127	306
Trucking	0	36	3	40
Water shipping	2	32	6	40
Electric utility	7,553	1,273	1,219	10,045
Gas utility	0	0	0	0
Wholesale trade	5	101	52	158
Retail trade	23	793	298	1,113
Real estate	0	474	138	612
Hotels	0	144	93	237
Restaurants	0	14	62	76
Health services	69	580	226	874
Government enterprise	1,151	493	706	2,350
Households	119	7,587	4,080	11,786
Federal government	160	989	147	1,297
State and local government	214	2,382	2,513	5,109
Total	16,343	21,386	12,874	50,603

Table 16.--Scenario 2: calculated fossil fuel balance by fossil fuel and sector

(In thousand dollars)

Sector	Fossil fuel balance			
	Coal	Fuel oil	Natural gas	Total
Iron mining	3,353	20,008	16,807	40,167
Highway construction	0	2,103	1	2,104
Well drilling	0	11,016	0	11,016
Maintenance	1	2,566	5	2,572
Meat products	19	203	118	340
Milk products	20	434	73	526
Frozen fruit and vegetables	0	458	175	633
Logging and sawmill	86	4,994	16	5,096
Pulp and paper	971	2,698	4,127	7,796
Chemicals 1	87	701	323	1,111
Chemicals 2	14	1,110	1,392	2,516
Chemicals 3	29	873	65	967
Petroleum refining	157	22,187	2,053	24,397
Asphalt and pavement	54	3,778	47	3,879
Miscellaneous stone	41	676	314	1,032
Blast furnaces	1,860	541	529	2,930
Railroads	0	6,335	133	6,467
Trucking	0	1,271	4	1,275
Water shipping	1	1,114	7	1,122
Electric utility	12,895	10,696	4,262	27,853
Gas utility	0	67	21,819	21,886
Wholesale trade	3	3,171	75	3,249
Retail trade	13	2,437	433	2,882
Real estate	0	1,457	200	1,657
Hotels	0	443	134	577
Restaurants	0	44	90	134
Health services	4	517	94	614
Government enterprise	71	439	293	803
Households	209	25,535	9,188	34,932
Federal government	10	882	61	953
State and local government	13	2,123	1,043	3,179
Total	19,907	130,877	63,880	214,663

Table 17.--Scenario 2: calculated fuel cost savings or (loss) by fossil fuel and sector

(In thousand dollars)

Sector	Fuel cost savings or (loss)			
	Coal	Fuel oil	Natural gas	Total
Iron mining	(312)	575	(208)	55
Highway construction	0	60	(0)	60
Well drilling	0	317	0	317
Maintenance	(0)	74	(0)	73
Meat products	(5)	60	(9)	46
Milk products	(6)	127	(5)	116
Frozen fruit and vegetables	0	135	(13)	122
Logging and sawmill	(96)	303	(1)	206
Pulp and paper	(1,085)	5,893	(51)	4,757
Chemicals 1	(8)	0	0	(8)
Chemicals 2	(1)	0	0	(1)
Chemicals 3	(3)	0	0	(3)
Petroleum refining	(15)	0	0	(15)
Asphalt and pavement	(5)	0	(4)	(9)
Miscellaneous stone	(4)	41	(23)	14
Blast furnaces	0	0	(7)	(7)
Railroads	0	153	(38)	115
Trucking	0	31	(1)	30
Water shipping	(1)	27	(2)	24
Electric utility	(3,255)	1,401	(153)	(2,007)
Gas utility	0	0	0	0
Wholesale trade	(2)	66	(2)	62
Retail trade	(10)	519	(9)	500
Real estate	0	311	(4)	306
Hotels	0	94	(3)	91
Restaurants	0	9	(2)	7
Health services	(31)	380	(7)	342
Government enterprise	(516)	323	(22)	(216)
Households	89	6,162	867	7,119
Federal government	(72)	648	(5)	572
State and local government	(96)	1,561	(79)	1,385
Total	(5,433)	19,269	218	14,055

ECONOMIC IMPACT OF SUBSTITUTING LOCAL WOOD ENERGY FOR IMPORTED FOSSIL FUELS

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This report summarizes our research to estimate the regional economic impact of using more wood fuels in place of some fossil fuels in northeastern Minnesota. The effect of such import substitutions is a common question facing economic development agencies. Our primary tools were an input-output model of the region plus an economic projection system called SIMLAB. Beginning with a base-line economic structure for the region in 1980, we made three projections of economic growth to the year 2000. The first projection portrays the region's economic structure in 2000 if fossil fuels were the almost exclusive source of energy. Two other projections portray the economy if two different scenarios of fossil to wood fuel conversions were achieved. Although the advantages of using locally produced wood in place of an expensive import would seem clear, some are not so obvious. In particular, if an import substitution can save money, the region's exports also become more competitive, in effect, a double-barreled advantage.

BACKGROUND

The study area, known collectively as the Arrowhead, consists of seven counties in northeastern Minnesota: Aitkin, Carlton, Cook, Itasca, Koochiching, Lake, and St. Louis. The Arrowhead region depends on four sectors: taconite mining, timber, tourism, and transportation. Although the Arrowhead uses much fossil fuel, it produces none; and it began to experience economic hardship during the OPEC oil crisis.

The region's economy may have begun to decline with the OPEC crisis, but accelerated when several taconite mines cut production or closed. As local authorities sought new sources of economic growth, it was not surprising that the Arrowhead's forests were seen as a likely base for development.

TWO ECONOMIC DEVELOPMENT STRATEGIES: EXPORT BASE ENHANCEMENT AND IMPORT SUBSTITUTION

There are two major ways to change a region's economic structure: export base enhancement and import substitution. Finding new ways to use taconite, such as the direct reduction of ore in the Arrowhead, or encouraging new investments in its pulp and paper industry, represent approaches to enhance the export base. Using wood instead of imported fossil fuels represents an import substitution approach. These two approaches are not mutually exclusive.

A region's prospects depend on its exports. Those exports bring in monies from outside the region, which in turn pay for any imports and for goods and services produced locally supporting its *export base.* Exports

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have a "multiplier effect", creating income that can be used to buy goods and services from local as well as export servicing industries. Money earned from exports is spent for several purposes such as savings and purchasing imported or local goods and services.

But savings and imports represent leakages from the region's income stream, and therefore, reduced multipliers. On the other hand, the more money spent locally, the greater the multiplier effect; thus, the advantage of *import substitution.*

This does not mean, however, that a region should always be self-sufficient. If a cheap import is replaced by a more expensive good produced locally, then import substitution increases the costs of its exports. And as a result the region's competitive position in the rest of the world declines.

There are two positive multiplier effects if a region can substitute cheaper, locally produced goods and services for those previously imported. First, new local production creates jobs and income. Second, the region's export multiplier increases. After a "good" import substitution is found, a region's export base becomes even more significant than it was before the import substitution. These two effects actually represent two facets of the same affect: increasing the ratio of local activity to export activity. This report projects the economic impacts of import substitution and the resulting export base enhancement in the Arrowhead.

Input-Output Models

An input-output model is a general equilibrium interindustry model originally developed by Wassily Leontief to guide national economic planning. Input-output systems are popular for both national and regional analysis especially because recent computer improvements make the process more affordable.

An input-output system consists of three basic tables. The first, the Transactions Table, traces interindustry sales and purchases within a defined region as well as by industry exports and imports to and from the "rest of the world". Developing this table is the heart as well as major expense of an input-output study. The second table, the Direct Requirements Table, shows for each industry, the proportion of purchases from every other industry required to produce one dollar of its output. It is easily calculated once the first table is complete. The third and most useful table shows the Total of Direct and Indirect Requirements and is so termed. This table is conceptually simple to calculate once the second table is complete.

This third table, also called the Leontief Inverse, allows us to determine the gross output for any regional industry, assuming any level of final demand for the same industry and assuming no technological change. In other words, projected changes in final demand for any one industry can be translated into changes in gross output for all industries in the region.

A key facet of input-output analysis is the use of interindustry earnings and employment multipliers that also form a key part of SIMLAB. These multipliers are derived from column totals in this third table.

SIMLAB Projection System

In contrast, SIMLAB is a system for simulating a region's economic growth and is based on an initial input-output model of a region's economy plus a set of parameters describing fundamental economic inter-relations and how they might change in the future. SIMLAB was developed at the University of Minnesota by Wilbur Maki and others. SIMLAB can be used to update an out-of-date input-output model to the present or to project an economy into the future.

Although an actual input-output study of the study region would be best, the expense of such efforts dictates that they can only be undertaken at wide intervals. And in fact, the input model of the Arrowhead is based on secondary data. Yet, many industries as well as public agencies often need to develop intermediate projections. These are very useful for developing strategies to enhance economic growth. Thus, the need for SIMLAB.

A SIMLAB model consists of several interrelated modules: outputs of one module are inputs for the next.

Many of the parameters assumed in the following modules can be changed and, as a result, many future economies can be projected. However, the following applications assume only one parameter set, which is held constant throughout. This set is regarded as fairly conservative and should not confound the wood energy projections with other factors expected to affect future economic structure.

* THE INVESTMENT MODULE estimates the region's capital requirements implied by each sectors' gross output in the input-output model. These estimates are in turn based on each sectors' need for new production equipment, pollution abatement, and repair and maintenance. Total investment for any sector is limited by its historical business income and retained earnings pattern.

* THE DEMAND MODULE estimates final demand for each sector based on previous estimates of the investment module, personal consumption expenditures from the population module, and government expenditures from the government module.

* THE MARKET MODULE estimates each sector's regional export to the "rest-of-the world" based on key

assumptions about national economic growth and regional market share. This module follows the export base notion of regional economic growth.

* THE GOVERNMENT MODULE estimates federal, state, and local government employment from estimated rates of employment change for the region. Government employment is also linked to regional population levels and economic activity.

* THE PRODUCTION MODULE takes the required regional output as given by the previous modules and feeds it to the Leontief Inverse of the region's input-output model. The result of this model is then compared to the output level possible with the amount of capital in the region plus new capital from the investment process. If the capital-constrained regional output is lower than the initial estimate of regional output by the demand module, the lower of the two values is assumed.

* THE EMPLOYMENT MODULE estimates employment and unemployment by occupation implied by the previous modules and based on each sector's assumed output per hour and average hours worked per week. These employment estimates then lead to in-or-out commuting in the short run and, in the following population module, to in-or-out migration in the longer run.

* THE POPULATION MODULE estimates the new regional population implied by gross output for each sector. These new population estimates are based on a starting population, birth and death rates, and estimated employment from the previous module.

* THE PRIMARY INPUT MODULE estimates the new regional earnings implied by the gross output of each sector. Earnings include employee salary and wages, business after-tax income, proprietor income, unemployment compensation, and transfer payments.

* THE HOUSEHOLD MODULE estimates housing requirements implied by the population calculated in the population module. Housing demand includes owner-occupied and rentals, and is measured using Census Bureau crowding and plumbing quality criteria.

Import Substitution and Input/Output-SIMLAB Interaction

We used the input-output model of the Arrowhead economy and SIMLAB in an iterative fashion to examine the impacts of import substitutions as well as future economic growth to the year 2000.

Step 1

The original 1977 input-output model was updated to 1980 because a local oil refinery had ceased operation by 1980. This update required us to construct a new transactions table to account for the expanded import of fossil fuels from 1977 to 1980. We then calculated the new Direct Requirements Table and the Direct and Indirect Requirements Table, the so-called Leontief Inverse. The resultant input-output model shows the Arrowhead's economy in 1980, depending heavily on imported fossil fuels.

Step 2

We next turned this 1980 economy over to the SIMLAB model, which projected the region's economic growth to the year 2000. As described above, this projection is based on a host of assumptions contained in the SIMLAB modules about such factors as national GNP growth, regional market share, and population growth. This projection is our so-called base line, table 1.

Step 3

We further modified the 1980 input-output model in a fashion similar to step 1 above. But in this case, we substituted locally produced wood fuels in various ways and amounts by various sectors for imported fossil fuels. As before, these changes were made to the transactions table, which was then used to calculate a new Leontief Inverse (the Direct and Indirect Requirements Table).

Two separate wood fuel expansion scenarios were developed for step 3, and therefore two more new Leontief Inverses were calculated. Although we assumed practically all sectors underwent some changes in fuel use patterns, two sectors changed the most: iron mining and electric utilities. Both sectors use much coal to produce electricity; the former for its own use and the latter for public consumption. Scenario A portrays these two sectors converting 15 percent of their coal use to wood. Scenario B portrays their converting 25 percent of their coal to wood.

Achieving these scenarios would reduce annual coal consumption by 28 or 35 percent respectively, oil consumption by 23 or 24 percent, and natural gas consumption by 16 or 17 percent.

Step 4

The two new Leontief Inverses of the Arrowhead economy, which now represent what the region's economy would look like in 1980 with less imported fuels and more wood energy, were also turned over to SIMLAB.

Under the same set of previous assumptions about future economic growth, SIMLAB then projected the Arrowhead's economy to the year 2000 for both scenario A and B.

Table 1.--Leontief output multipliers

Sector numbers	Industry	Base line	Scenario A	Scenario B
1	Dairy & Poultry Prod.	1.4720	1.4733	1.4738
2	Meat An. & Prod.	1.3667	1.3679	1.3684
3	Food, Feed Gr.	1.3208	1.3218	1.3220
4	Other Crops	1.3646	1.3658	1.3660
5	Forest., Fish, Prod.	1.1731	1.1734	1.1735
6	Agr., For., Fish. Serv	1.3422	1.3436	1.3441
7	Iron & Ferr. Ores	1.4247	1.4355	1.4385
8	Nonferrous ores	1.2162	1.2191	1.2205
9	Coal & Peat Mining	1.2179	1.2200	1.2209
10	Stone, Clay Mfg., Qua	1.2388	1.2414	1.2425
11	Other Mining	1.0000	1.0000	1.0000
12	New Construction	1.3639	1.3662	1.3663
13	Main. & Rep. Constr.	1.2698	1.2718	1.2719
14	Ordnance	1.0000	1.0000	1.0000
15	Meat products	1.4770	1.4795	1.4798
16	Dairy products	1.4667	1.4713	1.4717
17	Canned, Froz. Pres.	1.3581	1.3637	1.3642
18	Grain Mill. Prod.	1.4282	1.4291	1.4294
19	Bakery Prod.	1.2170	1.2180	1.2183
20	Alch. Bev., Soft Dr.	1.2217	1.2227	1.2229
21	Misc. Food, Tob.	1.2120	1.2131	1.2134
22	Textile Goods	1.2751	1.2767	1.2772
23	Apparel, Fab. Tex.	1.3022	1.3031	1.3035
24	Logging	1.2342	1.2511	1.2512
25	Sawmills	1.6710	1.6789	1.6494
26	Particleboard	1.4208	1.4247	1.4262
27	Other Wood Prod.	1.5648	1.5687	1.5694
28	Furniture	1.4340	1.4358	1.4362
29	Pulp & Paper Prod.	1.3971	1.4396	1.4407
30	Paperboard Cont.	1.2236	1.2265	1.2269
31	Printing & Publ.	1.5011	1.5074	1.5078
32	Chem. & Allied Prod.	1.3735	1.3779	1.3789
33	Petr. Ref. & Prod.	1.0919	1.0935	1.0938
34	Rubber Prod.	1.2376	1.2392	1.2398
35	Leather Prod.	1.2326	1.2335	1.2337
36	Glass, Stone, Clay	1.3304	1.3400	1.3408
37	Primary Fe/Steels	1.4429	1.4491	1.4503
38	Iron & Steel Found.	1.4354	1.4381	1.4390
39	Primary Copper	1.2745	1.2760	1.2765
40	Other Prim. Met.	1.4140	1.4170	1.4183
41	Fabricated Metals	1.3300	1.3316	1.3321
42	Farm Machinery	1.3113	1.3123	1.3126
43	Machine Shops	1.2611	1.2625	1.2630
44	Other Non. Electr.	1.3208	1.3219	1.3223
45	Comp. Off. Mach.	1.0000	1.0000	1.0000
46	Serv. Ind. Mach.	1.2549	1.2559	1.2562
47	Electrical Mach.	1.2462	1.2474	1.2478
48	Motor Vehicles	1.3163	1.3173	1.3175
49	Other Trans. Equip.	1.3210	1.3223	1.3227
50	Prof., Scient.	1.3620	1.3637	1.3641
51	Optical, Ophth., Pho	1.2641	1.2655	1.2658
52	Misc. Mfg.	1.3490	1.3507	1.3512
53	Railroad Trans.	1.3123	1.3177	1.3183
54	Local Transit	1.2027	1.2043	1.2047
55	Truck Trans.	1.1972	1.2002	1.2003
56	Air Trans.	1.1708	1.1716	1.1718
57	Other Trans.	1.4574	1.4644	1.4649
58	Communications	1.1590	1.1599	1.1602
59	Electric Utilities	1.2860	1.3579	1.4031
60	Gas Utilities	1.4532	1.4546	1.4547
61	Water & San. Serv.	1.2837	1.2879	1.2883
62	Wholesale Trade	1.1996	1.2020	1.2023
63	Retail Trade	1.1732	1.1810	1.1819
64	Finance, Ins.	1.3662	1.3677	1.3683
65	Real Estate	1.1705	1.1737	1.1739
66	Hotels, Pers., Rep.	1.2907	1.2991	1.3001
67	Business Serv.	1.2463	1.2471	1.2473
68	Eat. & Drink. Places	1.4456	1.4488	1.4495
69	Automobile Repair	1.2152	1.2162	1.2164
70	Motion Pic. & Recr.	1.3283	1.3296	1.3301
71	Health Services	1.2372	1.2454	1.2459
72	Educ., Nonpr.	1.3088	1.3117	1.3128
73	Fed. Gov't. Enter.	1.1291	1.1307	1.1313
74	State & Local Entr.	1.4822	1.5961	1.6005
75	Miscellaneous	1.4696	1.4710	1.4712

Table 2.--Wood energy development effects on employment, intermediate sales, and gross output

	Absolute and percentage changes from new wood energy sector in the year 2000			
	Scenario A		Scenario B	
	Million dollars	Percent change	Million dollars	Percent change
Employment				
Wood energy sector	332.0	101.3	352.0	110.6
Regional total-all sectors	2,500.0	2.7	2,752.0	2.9
Intermediate sales				
Wood energy sector	23.7	148.5	28.5	178.8
Regional total-all sectors	59.3	5.5	67.3	6.2
Gross output				
Wood energy sector	53.1	101.2	58.0	110.5
Regional total-all sectors	133.6	2.9	145.7	3.2

RESULTS

Differences between the base-line projection and the two import substitution scenarios, all for the year 2000, are shown in table 2. Differences are due entirely to the estimated changes in the region's transaction table because a significant portion of fossil fuel was replaced with wood. All values are in 1977 dollars.

As we would expect, substituting wood for fossil fuels has major impacts on employment, intermediate sales, and gross output in the region (table 2). The following comparisons are best examined from two perspectives: the effects on the region as a whole versus on the wood energy sector itself.

Impacts to the Region as a Whole

Between 2,500 and 2,750 new jobs would be created, about a 3-percent rise in employment. This increase reflects changes in both full- and part-time employees, because this kind of wood industry usually employs many part-time workers.

So too, this kind of wood industry is characterized by a very low capacity utilization. That is, if allowed to produce more, sectors could expand their output rapidly without increasing the number of direct jobs. The same number of workers would simply work more hours.

Intermediate sales in the region would increase $60 or $67 million, a 5.5 or 6.2 percent increase. This relative increase is larger than the employment increase primarily due to the capacity utilization concept just mentioned; although the number of new workers wouldn't be as large, fuel consumption, new equipment, and added transport etc. would all jump dramatically.

The value of gross output would increase $134 or $146 million, again about a 3-percent increase. The relative increase is not as large as intermediate sales because although intermediate sales would rise at the expense of imported fossil fuels, total economic output in most other respects would be substantially the same. That is, the increased output due to an expanded wood energy sector is simply spread over a larger total.

Impacts to the Wood Energy Sector

What is interesting here are the differences between the 15 percent and 25 percent coal to wood conversions. Differences between these and the base line are not quite as large as they appear, for although the starting point was low it was not really zero. Also we would expect a large jump.

Although employment and gross output differences between scenarios were both 9.3 percent (110.6 minus

101.3 and 110.5 minus 101.2), intermediate sales differed by 30.5 percent (178.8 minus 148.5). The 10-percent difference in coal to wood conversions by the iron mining and electric utility sectors has a fairly small employment effect compared to its effect on intermediate sales for the same reasons used to explain the differing impacts to the region as a whole.

In other words, although the development of a wood energy sector to displace imported fossil fuels would have a good impact on the region, the effect on jobs would not be as large as we might first expect.

Several final points need emphasis. Other portions of the research effort estimated the amount of wood available for energy and conventional purposes. These projections do not account for possible job losses in other wood products sectors due to a lack of wood. Nor do they deal with possible wood price changes resulting from increased wood use. Increased wood prices might make import substitution less efficient, even undesirable. But such an effect is doubtful, considering the surplus forest resource.

In input-output analysis, there are procedures for introducing local households into the industrial matrix which are termed, "...closing the table with respect to households." When such a procedure is carried out, the multipliers in the Leontief Inverse include an induced effect from household consumption.

Although no such procedure was used here, a type of induced effect does appear in the SIMLAB Demand Module. Household income was calculated as a function of the region's gross output. Income elasticities of demand were then applied to calculate household consumption from each of the 75 industries. This consumption then induces further output and employment for the region in addition to those coming out of the industrial component. Thus, stated employment impacts were larger than other models of a more static nature.

POLICY OPTIONS TO ENCOURAGE WOOD ENERGY USE IN NORTHERN MINNESOTA

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Wood is extremely important to the economy of Minnesota. The State's 13.6 million acres of commercial timberland are the source of wood fiber that is the prime raw material for more than 1,400 wood processing facilities. Minnesota's wood-based industry ranks among the State's three leading industries, employs more than 50,000 persons, and produces nearly $3 billion in product value.

The potential of wood residues has only recently been explored. Wood residues exist in many forms; trees and tree remnants after logging such as uncut stems remaining on the harvest site, and branches and tops, entire stands of low quality or dead trees, wood manufacturing waste, and urban wood waste from construction sites, or trees from lawns and boulevards. While these residues can be used in many ways, using them for energy has received particular attention. For many years, inexpensive fossil fuels discouraged the use of wood for energy, but as fossil fuel prices escalated rapidly during the 1970's, wood and wood residues were burned more frequently. Wood energy could supply between 8 and 15 percent of the Nation's future energy needs, a magnitude of considerable importance to a Nation attempting to reduce its dependence on foreign oil supplies (General Accounting Office 1981).

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BARRIERS TO WOOD-RESIDUE UTILIZATION

There are many complex obstacles to using more wood residues. Ironically, removing one deterrent may well lead to unexpected positive or negative consequences elsewhere in the technical and economic systems that determine wood residue use. Thus, policies must be carefully devised to enhance wood residue use without detracting from other forest uses. What follows is a general review of five major conditions influencing residue use. It is by no means complete, yet it provides an appreciation of factors that must be considered when new wood-residue policies are proposed (Wheatcraft *et al.* 1984).

Technical Barriers

Some technical barriers prohibiting expansion of wood residues for fuel can be linked to the lack of efficient harvesting equipment—especially small-scale equipment. An extensive amount of research has focused on improving harvesting technology in past decades, but the resulting equipment generally operates most efficiently on a large scale. A typical whole-tree chipping system, for example, costs nearly $1 million. Such costs can be prohibitive for small-scale loggers. Additional research is needed to develop equipment that will operate economically on a small scale. Ad-

vances in wood-burning technology have eliminated low efficiency and smoke as barriers to the use of wood residue as a fuel. Research funded by government agencies and tested and implemented by wood-based and related enterprises illustrate the effectiveness of government and private sector cooperation in dealing with technology of this sort. Wood storage and handling however, is an area that could benefit from additional research. Wood fuel is costly to handle because of its bulk and size variability and any savings from burning wood as a fuel may quickly be consumed by the added cost of storage and handling. Without additional research on such problems, the use of wood fuels may be hindered. Lack of high quality and reliable forest road systems often limit access to forests and thus make some wood residues uneconomical to harvest. Access problems are widespread deterrents to harvesting wood residue on both public and private forests.

Economic and Financial Deterrents

Depressed economic conditions experienced Nationwide during the past 2 to 3 years may be the single-most important factor impeding the development of wood energy. These conditions have curtailed demand for the products manufactured by wood-based enterprises and, consequently, have limited the need for energy required in manufacturing. High interest rates and high equipment costs also discouraged the purchase of residue harvesting and processing equipment.

Lack of venture capital also deterred wood energy development. Financial institutions are reluctant to extend credit to new and unproven businesses such as wood pelletizers, wood distributors, and wood energy harvesters. They may either refuse financial support entirely or charge a premium interest rate to cover the high risk. Although some capital is available through government agencies (e.g., Small Business Administration loans, Department of Energy grants), total investment capital at investment-inducing interest rates remains a problem.

Limited funding for wood residue research, marketing, and informational programs have also deterred wood energy development. Although federal agencies have invested heavily in research and demonstration projects during the past decade, current investments have been insufficient to make the technical breakthroughs necessary for more widespread use of forest residues.

Institutional and Administrative Conditions

Many institutional and administrative conditions impede the greater use of wood-residues. However, such barriers can often be overcome with minor changes in agency rules and regulations. Consider the following:

- Loggers and operators are discouraged from removing low grade or unmerchantable materials, i.e., wood residues, because of the public stumpage pricing procedures that lead to excessive stumpage prices.
- Public timber appraisal procedures establish minimum merchantability standards but do not consider economic and environmental benefits that may acrue if more usable wood (i.e., residues) were removed (General Accounting Office 1973).
- Public timber-harvesting administrators fail to enforce sale contract provisions that call for removing not only high value material, but also all wood material (including residues) as specified in the contract.
- Limited coordination among public agencies prevents establishing an action agenda to develop wood energy markets and encourage programs that logically flow therefrom. Due to the lack of coordinated and comprehensive regional plans for managing and using wood residue, no long-range outline can be focused on opportunities for utilizing such material.
- Wood residue users have limited assurance of reliable wood residue supplies at stable prices. Such conditions detract from investments in wood residue harvesting and burning equipment. Public and private forest landowners may be reluctant to make long-term contracts for a variety of reasons (e.g., others might construe this as an attempt to reduce competition, they fear that they would be unable to take advantage of rising future prices for wood and legal restrictions).
- Nonindustrial private forest landowners own 40 percent of Minnesota's commercial forest land. These owners control small, fragmented parcels of forest land, frequently espouse nontimber land management objectives, often have limited knowledge of forest management opportunities, and usually face severe financial limits on their ability to manage timberland. This creates difficulties for wood residue users who depend on these small parcels of land.
- Laws restraining prices of energy that compete directly with wood deter optimal flow of potential energy supplies. Regulating natural gas prices at an artificially low level results in consuming gas at the expense of other, really cheap energy sources such as wood residues.

Informational Constraints

Properly targeted and sustained flows of information about the availability of wood resiudes can encourage

their use. A major information barrier is the lack of wood residue price and production costs. Lacking such knowledge makes wood residue investments appear much more risky than they actually are and discourages investment in a viable and often profitable venture. Information voids are especially troublesome to potential investors evaluating new and untried energy sources and processes—such as wood residues. When compared with tried and proven energy technologies such as fossil fuel, wood residues appear riskier. Distributing information about the advantages and disadvantages of wood as an energy source can reduce this illusion of risk.

Adequate means of distributing existing information must be found. A central source for disseminating information to potential wood energy suppliers and users would be helpful. Another way to get information to potential users is to hold educational programs concerning wood residue availability and the best technologies for their harvest and use.

Environmental Concerns

Environmental concerns about increased wood use must be addressed. The more intensive timber management activities necessary to utilize wood residues (e.g., additional roads, removal of biomass) may have adverse effects on natural environments. Some people are also concerned about the uncertain effects of whole-tree utilization on future forest productivity and an increase in the level of air pollutants associated with certain forms of wood-burning equipment. All of these problems are controllable but may require troublesome and costly regulatory procedures.

PROGRAM PROMOTING WOOD USED FOR ENERGY

Federal Initiatives

General Accounting Office

The General Accounting Office (GAO) of the U.S. Congress periodically reviews selected National issues and suggests courses of action. Since 1973, the Office prepared two major reports addressing the use of wood residues. In both, the Office concluded that the Nation would be substantially better off if wood residues were more widely used for energy. The first report was issued in 1973 and recommended that federal land management agencies (i.e., USDA Forest Service, USDI Bureau of Land Management) take the following actions (General Accounting Office 1973):

- Modify federal timber sale procedures to ensure removal of economically usable wood that can be processed by facilities in the vicinity of the sale area.
- Establish methods and procedures for determining the amount of wood to be removed from the sale area so that the economic and environmental benefits from the increased use of wood will be recognized. Consider the feasibility of shipping the material outside the sale area.
- Ascertain the level of utilization possible under the best available timber processing technology.
- Analyze the effect of Federal assistance programs on increasing timber processing capabilities in areas where the timber resource is underutilized.
- Explore ways to increase wood processing capabilities.

In 1981, the General Accounting Office focused on specific opportunities for utilizing wood for energy. In a report entitled "The Nation's Unused Wood Offers Vast Potential Energy and Product Benefits" the Office urged the USDA Forest Service and the Department of Energy to place a higher priority on encouraging the use of wood for energy (General Accounting Office 1981). The report identified many barriers to increased wood fiber utilization that exist at the National level. Overall program recommendations were as follows:

- Conduct a cooperative program to assess areas believed to have the most promise for residue use. The assessments should inventory residue quantity and availability, evaluate potential residue uses, discuss barriers to increased residue uses, and propose ways to increase residue use. The USDA Forest Service should take the lead role in this assessment.
- Develop a National wood residue plan to be presented to Congress within 2 years. The plan should include residue use goals and recommendations for policy actions to overcome any barriers to achieving these goals.
- Continue to develop and demonstrate projects involving residue handling equipment.
- Develop standardized methods for evaluating the costs and benefits of wood fuel use in Federal facilities.
- Establish a program promoting the use of wood fuel. The program may involve demonstration projects, direct technical assistance, or educational materials.

The following recommendations were made specifically to the Secretary of Agriculture:

- Upgrade the forest survey to include an inventory of all potentially usable biomass.
- Request legislation that would authorize the U.S. Department of Agriculture to grant private firms either title or exclusive license to manufacture and

sell wood residue technologies developed by government.

- Adopt a more flexible policy regarding long-term contracts to assure that residues from National Forests will be available continuously.
- Reduce indiscriminate burning of piled material on the landings or as scattered logging slash.

USDA-Forest Service

The Forest Service has attempted to improve timber utilization standards for several decades and has recently been the Department of Agriculture's lead agency in efforts to develop programs to encourage wood residue utilization. In the Pacific Northwest tremendous volumes of wood fiber frequently remain after harvest. In the past, most of this fiber was burned in place—much to the detriment of air quality. The Forest Service instituted regulations in Federal timber harvesting contracts that required such material to be used—consistent with existing technology. Timber harvesters were required to concentrate unmerchantable material on harvested sites to increase its economic attractiveness to potential users. The Forest Service also instituted per acre pricing (lump sum) of small material, hoping that more material would be removed from the harvested site. Although these were positive steps, they placed an inordinate amount of the burden on timber purchasers. Without sufficient residue markets, purchasers were unable to sell the material.

The rapid rise of fossil fuel prices during the early 1970's led the Forest Service to further examine various potentials that wood fiber might have as an alternative fuel source. This examination led to further research in forest engineering, products utilization, economics and marketing. Such efforts resulted in a report entitled "A National Energy Program for Forestry" (USDA Forest Service 1980). Focusing on attaining a forest biomass energy production goal established by the U.S. Department of Agriculture, the Forest Service report defined five areas on which to concentrate:

- Produce current, accurate resource information. Incorporate total biomass measurements into inventory procedures.
- Improve resource supply. Apply improved forest management techniques.
- Develop equipment to recover forest biomass. Encourage improved forest biomass recovery by changing timber sales procedures.
- Improve conservation by substituting wood for other raw materials, increasing light frame construction, increasing management efficiency, weatherizing buildings, and processing wood products efficiently.
- Protect wood products from environmental degradation.

The program placed the Forest Service in a leadership position involving the utilization of wood residues for energy. Such leadership has been exercised through the Agency's biomass energy program implemented by reasearch, cooperative State and private forestry activities, and the National Forest system.

The Forest Service has also played an important role in establishing rules and regulations required by the Wood Residue Utilization Act of 1980. A special wood residue utilization program was established by the Forest Service to carry out the guidelines of the Act. The program has never been adequately funded, however, and will expire with little of its potential realized if the law is not reauthorized after a 5-year period.

U.S. Congress

The U.S. Congress has been active on the wood energy front by enacting several laws to promote specific aspects of wood energy production. Consider federal investment tax credits. Under the Energy Tax Act of 1978, investors receive a 10-percent federal tax credit when investing in wood energy facilities. The amount of the investment eligible for the tax credit depends upon the life of the facility and whether it is new or used. While the tax credit has a limit, excesses can be carried forward or back. Another tax incentive is the rapid amortization of pollution control facilities that can include plants utilizing wood waste or wood residues. And, lastly, the Economic Recovery Tax Act of 1981 increases depreciation rates for equipment used to cogenerate steam and electricity.

Congress also established financial programs to encourage investment in wood energy projects. Because these programs were in effect for only a short period of time, overall program effectiveness is difficult to measure. One such program provided credits for producing densified wood. The program was difficult to administer at the National level and led to capital investments in projects with an inordinately high level of risk and low chance of success. Congress also established financial support programs to convert schools and hospitals to wood energy.

In 1980, Congress sought increased utilization of wood residues by establishing the Wood Residue Utilization Act. The Act authorized the Secretary of Agriculture to conduct a 5-year pilot program to develop, demonstrate, and distribute information on feasible methods to increase and improve wood residue utilization. The program's thrust was to increase and improve wood residue utilization in residences, commercial businesses, industries, and powerplants.

Promoting cogeneration activities is another area where Congressional efforts helped overcome barriers inhibiting wood-energy growth. Cogeneration is affected by several Federal laws including the Public Utilities Regulations Policy Act of 1978 (PURPA), the Power Plant and Industrial Fuel Use Act of 1978 (FUA), and the Natural Gas Policy Act of 1978. The Federal Energy Regulatory Commission also has important cogeneration incentives. Under the Act, electric utilities must purchase electricity from qualifying cogenerators as well as sell electricity to them at nondiscriminatory rates. Interconnections must be established between the cogenerator and the utility's system. The Act also exempts cogenerators from certain regulations under the Federal Power Act and the Public Utility Holding Company Act. Legislative backing for the sale of electricity is important for cogenerators. Since enactment, the utility industry has challenged many of the Act's provisions in court, but most of the law's provisions have been upheld.

U.S. Department of Energy

The U.S. Department of Energy also plays an important role. It has been a leader in developing and funding various demonstration projects that have proven the reliability of wood-produced energy. In addition, the Department has coordinated the funding of resource availability studies and informational programs used to promote the direct combustion of wood. It has also funded research to improve harvesting and delivering forest residues.

State Programs

Several States promote the use of wood residues for producing energy and can serve as models for the State of Minnesota.

North Carolina Wood Energy Program

North Carolina has one of the most active programs for promoting wood energy, based on a coordinated plan to outline reasonable wood energy objectives. The plan was developed by a special task force established by the governor. The task force, known as the Wood Energy Coordinating Group, included members from the State's Department of Natural Resources and Community Development, Department of Administration, Department of Commerce-Energy Division, and the University of North Carolina.

The task force's early efforts included the aggressive pursuit of outside funding for demonstration projects, educational programs, and technical and financial assistance programs. This activity resulted in substantial funding by the U.S. Department of Energy, the U.S. Environmental Protection Agency, the North Carolina Energy Institute, the National Science Foundation, and other organizations.

Specific activities and responsibilities for the Wood Energy Coordinating Group were laid out in a master plan (North Carolina Wood Energy Coordinating Group 1978). These activities and responsibilities included developing markets for wood fuel, developing supply systems for wood fuel, developing research mechanisms, assessing the processes and techniques of using wood fuel, and analyzing the use of wood as a home fuel. Within these areas separate programs were developed for education, demonstration, technical assistance, and research.

The task force operated under the direction of a full-time Wood Energy Project Coordinator. Through the efforts of the task force, the State has encouraged a large number of energy-intensive industries (i.e., brick making and textile plants) to convert to the use of wood as their major energy source.

The North Carolina legislature has also promoted the use of wood for energy. Tax assistance legislation provides a 15-percent increase in depreciation to industrial concerns that convert from a fossil fuel energy system to a wood energy system. This allows more rapid write-off of wood burning equipment.

Along with work done by the wood energy task force, North Carolina has developed a strong extension program to promote wood energy. An extensive slide-tape presentation has been prepared to describe the disadvantages, advantages, supply issues, and other pertinent information for using wood. The program has been an effective tool for promoting wood energy development throughout the State.

North Carolina's success is based on the cooperation of the State's wood energy group and its university extension department. These group efforts have helped to alleviate the information gap concerning wood fuel and wood burning energy systems. The wood energy group's work is published in an annual report that provides an update on wood energy conversions and current research projects. The report provides information to the public and increases the awareness of the current situation concerning the use of wood for producing energy.

Oregon Wood Energy Development Program

The State of Oregon has taken a different approach to promote wood energy use. The State realized that utilizing waste wood or excess wood from timber harvests could significantly reduce pollution problems resulting from current wood residue disposal methods. Switching to wood energy was also perceived as a means to create jobs and reduce future energy demands. With these ideas in mind, Oregon developed a

program of tax incentives and financing programs to encourage investment in equipment to burn wood. Oregon carefully coordinates State programs with Federal programs.

Oregon offers a tax credit to reduce the cost of installing solid waste utilization facilities. This credit can be applied to facilities that convert wood waste into energy or other usable products and can also be used for additions to solid waste handling facilities that increase the production of energy from the plant. The amount of the credit differs with the life of the facility up to a maximum of 50 percent. Oregon also provides a 10-percent tax credit on certified investments in economically lagging areas. To qualify for the credit, investments must exceed $25,000 and the new facilities must have a reasonable expectation of creating new permanent jobs. These requirements can usually be met by larger wood energy conversion facilities. Lastly, investors receive a 1-year bonus of an extra 20-percent write-off on qualifying property. This write-off is in addition to the regular depreciation allowance.

Oregon offers a variety of financing options that may be used by wood energy project investors. These include a substantial reduction in the interest rate charged for borrowed capital used for wood conversion projects. The financing options depend on the sale of industrial development revenue bonds and are available from the State to finance certain business projects, from the counties for financing pollution control facilities, or from the various port districts for development within port areas.

The tax incentive and financing options create a positive investment climate for private firms in Oregon. Investments in producing wood energy are riskier than many other investments. Incentive programs serve to reduce risk and induce companies to make new capital investments. Oregon bears some of this risk and probably encounters a short-term decrease in tax revenues. However, if these programs stimulate significant investment, the State should reap substantial benefits in the long run.

Washington Wood Energy Directives

Although planning for wood energy in Washington has not been as extensive as in North Carolina and Oregon, significant actions have been taken. The latest timber management plan prepared for Washington specifically proposes using wood energy—if wood is the most economical use. This recognition places the use of wood energy on equal footing with other wood fiber uses. Additionally, the 1980 Washington legislature enacted a law requiring the Utilities and Transportation Commission to grant higher rates of return for utilities generating electricity by cogeneration or from renewable resources. The legislature also exempted wood energy production costs from a 3.6 percent Public Utility Tax.

PROGRAM AND POLICY OPTIONS

As we have seen, many program and policy options are available to encourage the use of wood energy. Following is a list—along with appropriate summaries—of major program and policy types that governments might use. An effort is made to describe new program types that could prove effective. Obviously, however, the ultimate combination of policies and programs must be designed with an understanding of the prevailing physical, economic, administrative, and political conditions. The following "laundry list" is presented as a means of displaying alternatives, realizing that many may be infeasible for one or more reasons (Wheatcraft *et al.* 1984).

Timber Harvest and Pricing Policies

Policies and regulations to guide public forest administrators can have a significant effect on wood residues use. Agencies frequently have difficulty in adopting rules and regulations to promote wood used for energy because, unlike private firms, their goals are not linked exclusively to maximizing revenues. Policies developed by public forest managers are constantly scrutinized by a variety of user groups having vastly different ideas of how public forests should be managed. Public agencies must continually balance policies so that a particular group is not unduly favored. In such an environment, administrators must be especially creative and innovative. In the following sections, policy changes in timber harvest regulations and stumpage pricing fees are explored that may encourage increases in forest residue utilization. Strong administrative leadership will be required if these ideas are going to be accepted by the public.

Long-term Residue Harvesting Contracts

A major barrier to increased wood energy development may be the lack of guaranteed fuel supplies at reasonable and stable prices. A possible solution to this problem would be to develop long-term residue removal contracts with public agencies managing forest land (contracts guaranteeing residue removal rights for up to 10 years at an agreed-upon stumpage fee). With a guaranteed supply and a fixed price, a wood energy supplier could provide information for potential users so they can assess the competitive position of wood fuel in relation to their current fuel. This information is

essential to determine the potential gains from using wood. Without guaranteed supplies, wood energy users face unknown risks of wood fuel shortages or rapidly escalating wood prices. Reducing this risk may be a key element.

A long-term residue removal contract could be written to include only residues from harvested sites or it could include the rights to material in otherwise unmerchantable low-quality stands. Interest in pursuing the use of long-term residue removal contracts as a means of increasing fiber utilization is not widespread in the public sector. Reasons for this lack of interest include: (1) loss of control over land use when contract rights are given for long periods, (2) risk of revenue loss if wood fiber prices rise significantly, and (3) realization that long-term contracts would favor one resource-using sector over all others. These concerns are important and when combined may seriously limit the use of long-term contracts.

Reducing Stumpage Prices

Reducing stumpage prices or even negative pricing may be necessary to encourage removing the residue that would otherwise be left in the woods. Many benefits accrue from increasing the level of wood residue utilization. These potential benefits include: (1) recovering material already paid for through land management activity and fire protection, (2) adding new revenue to loggers—however small, (3) reducing the regeneration costs for establishing the next timber stand, and (4) capturing a forested area's future productivity, which may be foregone without price incentives. If lower prices for residue are found to be the key link to increase utilization, consideration should be given to such an approach. The benefits from increased utilization could be set against the loss in revenue or the cost of the subsidy. The price of residue could be set so that benefits are greater than any costs incurred. This simple concept to encourage greater resource use is often resisted because the public may perceive it as giving timber away. If this perception did develop, it could damage the efforts of public forest administrators to properly manage the forest resource. This problem, however, could possibly be eliminated with a program to detail the benefits of reduced stumpage prices or negative pricing.

Reduced prices could be instituted on a trial basis in an area that presently has an active wood energy market. During this trial, an appropriate pricing system for residue removal could be developed. Using open bidding for residue sales could encourage a free market activity in which an optimal price could be established.

Joint Timber Harvest Scheduling

Public agencies managing timber on land owned by several parties could schedule timber harvesting for all or selected portions of the forest land. Such action may encourage more efficient management of the timber resource and could increase wood residue utilization. Larger timber sales may encourage the use of more economical wood residue recovery equipment. Opportunities for securing better, less costly access to forest sites and the availability of larger volumes of residue material could encourage more efficient use of whole-tree harvesters and related equipment. Timber purchasers could be spared the costly and time-consuming process of moving from one small site to another.

Joint timber harvest scheduling could only be accomplished with substantial cooperation among local, State, and Federal forest landowners. Their differing goals, perspectives, and clientele may preclude such cooperation. Small-scale cooperative efforts, however, could be tested. If the approach proves ineffective, the cost of failure would be small.

Long-term Planning

Recognizing wood energy and wood fiber utilization goals in long-term forest planning processes is an additional method for improving wood residue utilization. Incorporating such goals would allow forest managers to focus on residue utilization goals and a means of achieving them. Including potential benefits and costs of increased wood residue use in Statewide forest plans would alert forest managers to the possible impacts of such a use. With proper planning, negative impacts could be reduced while the full potential of positive impacts could be realized.

Transportation Systems

Improving wood residue utilization depends on an adequate transport system including forest roads, State highways, rail, and water transport systems. Suggestions for improving transportation systems at the State level have been suggested (Commission on Wood Products 1983). The [Minnesota] Governor's Commission on Wood Products recommended the following six-point program in 1983:

- Finance road improvements according to the "State Forest Road Plan."
- Increase the priority of State and county highway improvements within the forested areas of the State.
- Support and improve the "Minnesota Rail Service Improvement Program."
- Permit a 10-percent tolerance in forest products vehicle weights if loaded in woods or other places where scales are not available.
- Investigate opportunities to improve forest products shipping.
- Standardized State and Federal load width standards.

Road and other transportation improvements require substantial amounts of capital from State and Federal governments. Such large capital investments are unlikely unless funds from gasoline and highway taxes become available. Improved transportation is not the major barrier to increased residue utilization. Yet without substantial improvements in current transportation systems, forest residue utilization will be inhibited.

Heating Government Facilities With Wood

County, State and Federal governments can make a stronger statement about wood fuels by using wood energy themselves. At the present time, few government agencies have examined or actually installed wood-burning boilers or generators. Although there is some risk, the number and history of current wood fuel users should indicate its reliability. Considering the many potential benefits of increased wood fiber utilization, State officials could easily assume the lead in this respect. Such actions may be a dramatic catalyst for developing a wood fuel market and bringing wood into the forefront as a major alternative fuel source within Minnesota.

Wood Energy Specialists

Specialists in wood residues and wood energy could enhance wood residues use. These persons could be assigned to the staffs of the Minnesota Department of Natural Resources, the University of Minnesota, and county governments where they would concentrate exclusively on pursuing innovative methods and programs to stimulate increased utilization of wood energy. Using wood energy specialists has proved to be successful in other parts of the nation—wood residues used for energy increased dramatically as a result of staff promoting wood as an alternative fuel source. Hiring wood energy specialists would require government funding but costs are modest. The positions could be temporary (i.e., approximately 5 years), after which time the wood fuel market should be sufficiently established so that government support is no longer necessary.

Tax and Financial Policies

The area of tax and financial incentives is a complex area and provides many opportunities. Incentives must be carefully designed to prevent subsidization of overly risky proposals or to pay for projects that would "normally" occur without government assistance. Tax programs should not create unwieldly administrative problems nor lead to fiscally irresponsible allocations of public capital.

Government Guaranteed Loans

The capital cost of wood energy systems can be prohibitive given the high and often unknown risks associated with such investments. With government guaranteed loans the risk to a lender is significantly reduced. And by lowering the risk, private lenders are encouraged to lower the interest rate charged to wood energy projects. Positive results may be achieved with minimal costs if loan application approvals are carefully monitored. Loan guarantees can serve as a low-cost method to spur development within the wood energy market.

But government loan guarantees also have problems. When a guaranteed project fails, the public is required to repay the privately financed loan. Sound program administration is the key to limiting such defaults.

Increased Local Funding

Wood energy projects can be increased by direct local government financial support. In Minnesota, the Iron Range Resources and Rehabilitation Board (IRRRB) and the Arrowhead Regional Development Commission (ARDC) have provided development capital to energy projects. Here, too, financial support must be directed to projects offering the highest probability of economic benefits, i.e., those that create jobs, increase local income, and have the lowest risk.

Tax on Non-wood Energy Sources

Coal is not mined in Minnesota. An import tax on coal shipped into Minnesota could have several advantages. First, it could provide an incentive for using wood-produced energy. Second, it could have a positive effect on economic development in the depressed areas of northeastern Minnesota by employing more loggers, truckers, and related service people. Third, it could lessen the extent of the acid rain problem because coal has been identified as a major contributor to this problem.

A coal import tax also has serious disadvantages. Its adoption would be very controversial and would definitely meet strong opposition from coal-using energy producers and possible retaliatory import taxes on products shipped from Minnesota. Because little is known about the relation between the size of such a tax and its effect on wood used for energy, a coal import tax may be highly counterproductive. Then, too, economic development may be reduced as a result of increased energy costs. Some sectors, such as iron mining, that use large amounts of coal for energy may be placed under excessive pressure considering their already tenuous hold on profitability. It would seem more logical to seek ways of lowering their costs rather than raising them.

APPRAISING PROGRAM AND POLICY OPTIONS

Many policy and program options are available for encouraging the use of wood residues, each has advantages and disadvantages. To wisely choose from among such options, they must be systematically evaluated. Following is an evaluation; it was prepared by defining the evaluation criteria, summarizing program approaches previously discussed, applying criterion to program options, and developing observations and conclusions. The criteria used to judge program and policy options were (Wheatcraft *et al.* 1984):

- importance of problem (barriers) to the utilization of wood residues
- financial investment (public sector only) required to carry out the program
- government coordination required
- degree to which the program area will encourage wood residue utilization
- degree to which the program area will enhance economic activity (e.g., employment, income, stability)
- likelihood of success
- cost effectiveness
- period of time over which program area would be accepted and adopted
- potential acceptability by government, wood industry, and the public.

The ratings we assigned were: H = high; M = moderate; L = low; and NA = not applicable. Because empirical evidence relating criterion to program areas is limited or nonexistent, the ratings are highly subjective. Furthermore, because the scale of program areas differs markedly (e.g., deregulation of fossil fuel prices versus a new wood utilization extension position), it is difficult to judge the outcome of a program. And last, alternative program areas are evaluated in a discrete fashion; certainly combining program areas would result in synergistic effects (table 1).

A Policy Program Proposal

Public programs to enhance wood residue use would provide benefits that probably would not have been achieved if left to traditional market systems. But public involvement to encourage wood residue use must be well designed and properly planned. A thorough understanding is necessary of public program objectives and the steps necessary to achieve them. Expectations should be realistic so that the risk of failure is minimal. Because programs to enhance wood residue utilization are new and often untried, they should be designed with some flexibility so as to accommodate unforeseen technical, economic, and administrative events. Program managers and planners must carefully monitor progress toward agreed-to objectives. Implementing wood utilization programs will require the involvement of many user and problem-solving groups (USDA Forest Service 1980). Federal, State, and local land managing agencies; universities; private consultants; research organizations; industrial entities; and trade and dealer associations must communicate and coordinate efforts to achieve program objectives efficiently and effectively. In addition, program success at the State level will rest heavily on:

- legislative appropriation of State funds,
- governor's personal leadership,
- State university participation via research and extension programs,
- State and county forest management agencies working to support the use of wood for fuel, and
- visible demonstrations of wood supply and commercial, industrial, and institutional applications within the State.

With the above criteria in mind, a set of policies and programs to encourage the use of wood residues in Minnesota can be developed. It should not be viewed as "the final word" but rather as a starting point for discussion and debate. Specifically, a wood residue program in Minnesota could entail the following:

- develop a wood energy plan under the direction of a wood energy coordinator,
- emphasize educational and technical assistance programs to promote wood energy,
- convert public buildings to wood energy,
- plan forest management programs focused on wood residue,
- provide long-term contracts for sale of residues or otherwise unmerchantable public timber, and
- develop a guaranteed loan program for investments in wood energy projects.

The most important step in establishing a wood residue program is to develop a wood energy plan. Such a plan should outline goals, describe programs and resources required to implement it, and focus on northeastern Minnesota. The plan should be constructed with input from all interested parties and should describe the level of effort expected from each participant. It could best be developed under the leadership of a designated wood energy coordinator and should focus State efforts on especially meritorious projects. Cogeneration, large- and small-scale process steam projects,

Table 1. Appraisal of public programs to promote the use of wood residues in the production of energy.

Program Areas	Appraisal Criteria: Importance of Problem Area	Cost of Implementing	Government Coordination Required	Impact on Residue Utilization	Economic Impact	Likelihood of Success	Cost Effectiveness	Timing of Adoption & Impacts: Near Term	Short Term	Long Term	Potential Acceptability: Government Policy Makers	Public Forest Managers	Wood Industry Officials	General Public
EDUCATION														
A. Expand forest landowners' knowledge of forestry and wood residues	M	L	H	L	L	L	M	L	M	M	H	H	H	H
B. Expand knowledge of wood energy among														
- public agencies	H	L	H	M	M	M	H	M	H	H	M	H	M	H
- small businesses	H	L	H	M	M	M	M	L	M	H	H	H	M	H
- large businesses	L	L	H	L	L	M	M	L	M	M	H	H	M	H
- residential consumers	L	L	H	M	L	L	L	L	L	M	H	H	H	H
C. Increase training of wood harvesting labor force to improve utilization efficiency	M	L	M	M	M	M	H	L	M	H	H	H	H	M
D. Develop and expand technical assistance workshops on wood burning technology	L	L	L	L	L	M	M	L	M	H	H	H	H	H
E. Encourage wood industry to increase educational assistance on wood residues	M	L	L	M	L	L	H	L	L	L	H	H	M	H
F. Establish and fund wood utilization extension specialist	M	M	L	M	M	M	M	L	M	M	L	H	H	M
G. Establish and fund wood energy utilization extension specialist	M	M	L	M	M	M	M	L	M	M	L	H	H	M
REGULATION														
A. Establish stringent wood utilization standards for														
- public forest land	M	M	M	M	M	L	M	M	M	M	M	L	L	H
- private forest land	M	M	M	M	M	L	L	L	M	M	L	L	L	L
B. Deregulate price of all fossil fuels	H	L	H	H	H	M	H	H	H	M	M	NA	L	L
C. Strictly enforce rules requiring public utilities to purchase cogenerated power	H	L	H	L	M	H	H	L	L	L	M	NA	NA	H
FINANCIAL														
A. Tax incentives														
- investment credit	M	H	M	M	M	M	M	L	M	H	M	M	H	M
- accelerated depreciation	M	H	M	L	L	L	L	L	M	M	M	M	H	M
- production credits for wood fuel	L	H	M	L	L	L	L	L	L	L	L	M	H	L
- pollution control credit	M	H	M	L	L	L	L	L	L	L	L	M	H	M
B. Financing														
- revenue bonds	H	M	M	H	M	H	M	M	H	H	L	M	H	M
- loan guarantees	H	M	M	H	M	H	M	M	H	H	L	M	H	M
TECHNOLOGY														
A. Expand research on:														
- wood residue harvesting equipment	H	H	M	H	H	M	M	L	M	H	L	H	H	M
- wood residue delivery equipment	H	H	M	H	H	M	M	L	M	H	L	H	H	M
- wood fuel combustion efficiency	L	H	M	M	L	L	L	L	M	M	L	M	M	M
ADMINISTRATIVE														
A. Prepare and adopt statewide wood energy plan	H	M	H	H	M	H	H	M	H	H	H	H	H	H
B. Identify wood residue objectives and programs in long-term timber management plans	M	L	M	M	L	H	H	L	M	M	M	H	H	H
C. Intensify state and regional forest resource studies	M	L	M	L	L	M	M	M	M	M	M	H	H	M
D. Establish and fund wood energy coordinator position	H	M	L	H	H	H	H	M	H	H	M	H	H	H
E. Develop and expand use of wood energy demonstration projects	H	H	H	H	H	M	M	L	M	H	M	M	H	M
F. Encourage use of wood generated energy in public buildings	H	L	L	M	M	H	H	M	H	H	M	H	L	M
G. Increase funding emphasis on														
- reforestation	H	M	M	L	L	M	M	L	M	H	M	H	H	M
- forest management	H	M	H	H	H	M	H	M	H	H	M	H	H	M
H. Improve and expand forest road systems	H	H	H	M	M	M	L	H	M	M	L	H	H	L
I. Adopt joint scheduling of public timber harvests	L	M	H	M	L	L	L	L	L	L	L	L	M	M
J. Initiate new residue pricing policies														
- negative pricing	M	M	L	H	M	H	M	M	H	H	L	L	H	L
- residual removal credits	M	M	L	H	M	M	M	M	M	M	M	L	H	M
K. Establish long-term wood residue utilization contracts	H	L	L	H	H	M	H	L	M	H	L	L	M	M

* Ratings of program areas are: H = high, M = moderate, L = low, and NA = not applicable.

and district heating programs are worthy of attention. Small-scale process steam projects appear to have special merit for the use of wood residues.

In addition to designing a wood energy plan, establishing a wood energy marketing system also is essential. Only through the use of such a system can the cost of wood biomass become competitive and supplies to consumers be dependable. As previously discussed, consumer apprehension about wood fuel supplies is a major factor limiting conversion to wood energy. Wood energy conversions in public buildings and forest management activities designed to assure residue supplies could enhance marketing projects. Extension programs may be a good way to inform wary consumers of wood energy opportunities.

Public forest management and timber harvesting programs should encourage reliable and accessible supplies of wood residue for energy. Harvesting low quality, understocked, or stagnant timber stands could create substantial wood residue supplies and allow more intense timber management practices in newly established stands. Long-term wood residue removal contracts may encourage wood-residue use.

State authority to develop and implement a loan guarantee program encouraging investments in wood energy projects should also be considered. If properly administered, such loans could ease the investor's financial burdens by enabling lending institutions to charge lower interest rates—rates consistent with the real risk. Such a program could involve limited State financing if projects are wisely chosen and mechanisms for collecting administrative costs are established.

Minnesota is faced with an opportunity to enhance the use of wood in a fashion that will encourage energy conservation and economic development. This opportunity is especially noticeable in the State's northeastern region. The resources required to capture such an opportunity are not overwhelming, so investing in a comprehensive wood residue utilization program should be seriously considered.

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ENGINEERING AND ECONOMIC CONSIDERATIONS OF WOOD ENERGY SYSTEMS USING WOOD CHIPS AND PELLETS[1]

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Wood alone cannot remedy future shortfalls in the Nation's energy supply. Rather, wood belongs to the growing category of supplementary fuels that together will fill this gap. In addition to providing an alternative energy source, the use of wood fuel can result in annual cost savings for a facility, have a positive economic impact on local and regional areas, and improve forest management practices.

The use of wood for energy has continued to increase since the early 1970's—first in the forest products facilities that had existing residues and more recently in other industrial, commercial, and institutional applications. Recently the rate of conversions to wood fuel has declined partially due to stabilized fossil fuel prices, and the fact that many of the most cost effective conversions have already been completed. But as fossil fuel prices continue to rise, conversions will again increase.

Although wood fuel is not a solution to the energy needs of all facilities, in many cases it may provide an economically viable alternative to fossil fuels. The primary benefits of using wood as an energy source are as follows:

1. Fuel cost per million Btu is usually significantly lower than other fuels.
2. Wood, when burned properly, does not create appreciable air pollution.
3. Wood can be a more reliable fuel source than fossil fuels under certain conditions.
4. Local wood production creates more jobs and retains more energy dollars in the State than fossil fuels do.
5. New opportunities for marketing low-quality wood could improve the profitability of stand conversions, precommercial thinnings, and other forest improvement operations which would result in the production of higher value timber at lower cost.

This paper provides a summary of a study conducted to analyze the equipment requirements and the delivered energy cost of wood energy systems using wood chips and pellets (Steklenski and Haygreen 1983). In addition, we analyzed how wood fuel price, interest rate, and non-fuel annual cost would affect the total annual cost of each system.

WOOD ENERGY SYSTEM EQUIPMENT

The development and production of equipment used in wood energy systems has advanced dramatically over the last 10 years. Current systems can be designed to be highly automated and with routine maintenance will be very dependable. However, there are inherent limitations with equipment designed for use with wood fuel. One cannot expect even the most automated wood energy system to be as easy to operate as a natural gas or oil system, but that gap has been reduced significantly. The success of each system depends substantially on the engineers that design that system and oversee its installation. Many engineering firms have gained a wealth of knowledge, and it is important that this knowledge be put to use.

[1] *Wolf and Associates, Inc., St. Paul, Minnesota, served as a consultant during this study. A cooperative study by the Department of Forest Products, University of Minnesota; and Research Work Unit FS-NC-4802, North Central Forest Experiment Station, Forest Service, USDA, Duluth, Minnesota. Partially funded by Forest Service, USDA, under Cooperative Agreement No. 23-82-18.*

Wood energy system equipment can be divided into two general categories: (1) handling, preparation, and storage equipment and (2) energy conversion and pollution control equipment.

Wood fuel is bulkier and of lower energy density than fossil fuels. Therefore, to provide adequate fuel inventories, handling and storage equipment is an important part of any wood energy system. It is in this area that the most equipment failure has occurred. Most problems occur when wood fuels that differ from design specifications are passed through a system. Three of the most important fuel parameters that relate to the operation of storage and handling equipment are fuel size, moisture content, and bulk density. A system designed specifically to store and handle a densified wood fuel such as pellets won't operate, in most cases, with wood chips or bark. A system could be designed for multiple fuels, but that decision should be made in the initial engineering phase of the project. Therefore, wood energy users should be aware of their fuel supply situation and design and operate their system accordingly. One method of assuring this is to incorporate specifications of the above mentioned fuel parameters in all fuel purchase agreements.

Despite past problems with storage and handling equipment, great advancements in equipment and system design have taken place in recent years; with careful planning, a reliable handling and storage system can be built.

Energy conversion equipment is often similar to that used for coal burning systems. In some cases existing fossil fuel combustion systems can be retrofitted to burn wood at a fraction of the cost of a new wood combustion system. As with handling and storage equipment, wood combustion equipment is now being designed to account for the unique properties of wood fuels and is therefore able to handle a wider range of wood fuels more efficiently. However, every wood combustion system does have limitations in regard to the fuel moisture content, size, and ash content at which it will operate. Therefore, the system must be carefully designed if it is to operate efficiently.

Currently, particulate matter and visible emissions appear to be the only emissions of concern produced by non-residential wood burners. The quantity and quality of these emissions is very site specific and depends on the type of combustion system, fuel type, and operating conditions of the burner.

Visible emissions are the result of poor combustion control, fuel variances, operator inexperience, misapplication of burner design, or some combination of the above (Junge 1977). Control of visible emissions, therefore, is often a matter of improving the operation of the combustion system.

Particulate emissions, which include fly carbon and inert materials, are a function of boiler firing practices and the amount of inert material entering the furnace. Particulate emissions range from less than a sub-micron up to 2 millimeters in size (Junge 1979). Some form of particulate emission control is generally required if a combustion system is to comply with State and Federal air quality regulations. This control may take place within the burner or after combustion gases exit the burner. In most cases particulate emissions can be kept at acceptable levels with commercially available equipment.

ECONOMICS OF WOOD AS A FUEL SOURCE

It is useful to review the basic economic framework of a decision to convert from an oil or natural gas system to a wood fuel system. We can compare the two systems in the following ways:

Oil/natural gas	Wood
1. Expensive fuel	1. Inexpensive fuel
2. Easy to use	2. More difficult to use
3. Inexpensive to convert	3. Expensive to convert

Wood fuel is economically attractive because it is less expensive than oil or natural gas on a net energy basis. A decision to convert to wood fuel is made if the anticipated fuel cost savings are sufficiently greater than the incremental increases in capital investment cost, operating and maintenance costs, and other miscellaneous costs. The following section provides general information regarding the above cost factors.

Fuel Cost

Fuel price depends on type of fuel, moisture content, quantity purchased, transportation distance, local supply and demand situation, and type of fuel processing. Typical prices range from $10 to $25 per ton for wood chips and from $50 to $60 per ton for densified wood fuel.

Wood fuels are commonly purchased on a dollar per ton basis; however, to account for the significant effect moisture has on a fuel's usable heat, it is more appropriate to compare fuel cost on a dollar per million Btu basis. Equation [1] is used to calculate fuel cost on the dollar per million Btu basis. As can be seen from this equation, moisture present in the fuel, the associated conversion efficiency, and the heating value of a fuel are accounted for in determining fuel cost.

Table 1.--Comparison of fuel costs for various fuels

(In $/million Btu)

Fuel type	Cost (Dollars)	Heating value	Moisture content	Efficiency (Percent)	$/MMBTU
Natural gas	4.65/MCF	MMBTU/MCF	--	0.80	5.81
#2 oil	.90/gal	138,000 BTU/gal	--	.80	8.15
Wood pellets	60/dry ton	17 MMBTU/dry ton	0.08	.78	4.92
Wood chips	20/dry ton	17 MMBTU/dry ton	.45	.65	3.29

$$\$/\text{MMBTU} = \text{Fuel cost (\$/unit)} \times \frac{\text{Unit}}{\text{MMBTU}} \times \frac{1}{(1-\text{MC})} \times \frac{1}{\text{Conversion Efficiency}} \quad [1]$$

The fuel costs, using equation [1], of various fuels are compared in table 1. Wood fuels, at these selected fuel prices, have a significant cost advantage over oil and natural gas.

Capital Investment Costs

The capital investment required for the conversion of a facility includes the cost of the following equipment:

1. Unloading
2. Fuel handling and storage
3. Energy conversion
4. Pollution abatement
5. Control systems

Additional capital investment may be required for constructing buildings and roads, or modifying an existing structure. Captial investment cost of a wood fuel system ranges from 2 to 10 times that of a similar size oil or natural gas system and is primarily influenced by system capacity, fuel type, type of equipment used, degree of automation, system flexibility, and site-specific factors (MN DEPD 1983).

Installation Cost

Installation cost generally represents from 10 to 50 percent of the capital equipment cost and depends on the type of equipment to be installed and site-specific factors. However, these costs have been reduced for many small to medium, wood energy systems through modular construction techniques and systems that are almost completely shop fabricated.

Operating and Maintenance Costs

The operating and maintenance costs for wood fueled systems vary with fuel type, equipment selection, degree of automation, and maintenance schedule. These costs will be several times greater than those of equivalent size oil or natural gas systems because of increased labor requirements, maintenance costs, and electrical power requirements.

More labor is required to remove ash from the fire box and to clean the boiler more frequently than with oil or natural gas. The increase in equipment to store and handle wood fuel can increase maintenance costs approximately 200 percent (MN DEPD 1983). Increased electrical costs are due to the need for electrical motors for handling equipment, the combustion unit, and pollution control equipment. The incremental cost associated with these power requirements depends on the size of the system and the electrical energy rates.

Miscellaneous Costs

In addition to increased operating and maintenance costs, wood energy systems may also face increased insurance costs and property taxes. However, this is very site specific and should be carefully evaluated by each facility contemplating a conversion to wood fuel.

As mentioned above, a decision to convert to wood fuel is evaluated on the basis of anticipated annual fuel cost savings versus the incremental increase in capital investment cost, operating and maintenance costs, and other miscellaneous costs. Therefore, any policies or legislation that can enhance one or more of these economic factors will likely increase the number of facilities converting to wood fuel. But in some cases, even with such incentives, a facility may chose to continue to use oil or natural gas because of convenience, the desire to concentrate on the primary business interests, or simply a resistance to change.

ECONOMIC ANALYSIS

The purpose of the research described below was to investigate the economic relationships associated with wood energy systems and to determine cost and engineering information for a wide range of potential wood fuel users. In addition, results of the economic sensitivity analysis can be used as a guide for developing public policy or legislation that will provide suitable incentives to increase the quantity of wood used as fuel.

The project did not directly compare wood fuels with fossil fuels because many existing studies conducted this type of analysis or provided the necessary procedures to do so (Banta 1979, Ekono Inc. 1982, Harpole *et al.* 1982, McGowan and Walsh 1980, and Pulaski *et al.* 1981). Additionally, such comparisons are commonly very site specific and of limited use for most potential wood energy users.

Six energy systems ranging in output from 0.4 to 200 million Btu per hour were analyzed in detail to develop a broad range of costs for chip and densified wood energy systems. A densified wood fuel system was not considered for the 200 million Btu per hour system because of difficulties that would be associated with supplying the approximately 100,000 tons of densified wood fuel required annually. The capacity, use, and potential users of each system studied were:

System Capacity (10^6 Btu/hr)	Use	Potential Users
0.4	Space heating	Small commercial buildings (i.e. small apartment building, store, office)
0.8	Space heating	Medium commercial building
7.5	Space heating	Large commercial, school, or hospital building
25	Space and process heating	Medium industrial and heating district heating
90	Space and process heating	Large industrial and district
200	Space and process heating	Pulp and paper mill

We used a method of analysis based on current costs to evaluate each energy system. The cost of each system is reported as the annual cost per million Btu per year and is termed the delivered energy cost. This method allows for easy comparison of alternatives within and between systems. Alternative assumptions analyzed include variations in fuel type, storage capacity, fuel price, interest rate, and non-fuel annual cost.

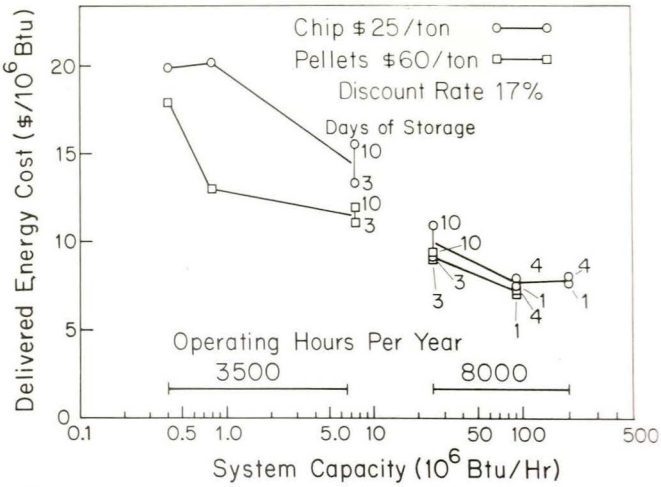

Figure 1.—*Delivered energy cost of densified wood and chip fuel energy systems for six representative energy users.*

The assumptions regarding equipment selection and cost calculations for each system are presented in detail in Steklenski and Haygreen 1983. These assumptions were developed from the following sources: (1) equipment manufacturers, (2) engineering firms, (3) existing wood energy systems, and (4) published information. Because of the site-specific nature of wood energy systems, these assumptions represent only one of many design possibilities and may be altered to accommodate other scenarios. In addition, sufficiently detailed cost information is provided so that other economic analysis methods can be used if desired. If a site-specific evaluation of economic feasibility is required, several computer programs are available for wood energy economic analysis (Harpole *et al.* 1982, Laulainen 1981, and Pulaski *et al.* 1981).

Delivered energy cost and annual cost information for the range of chip and densified wood fuel systems considered is summarized in figures 1 and 2. Given the

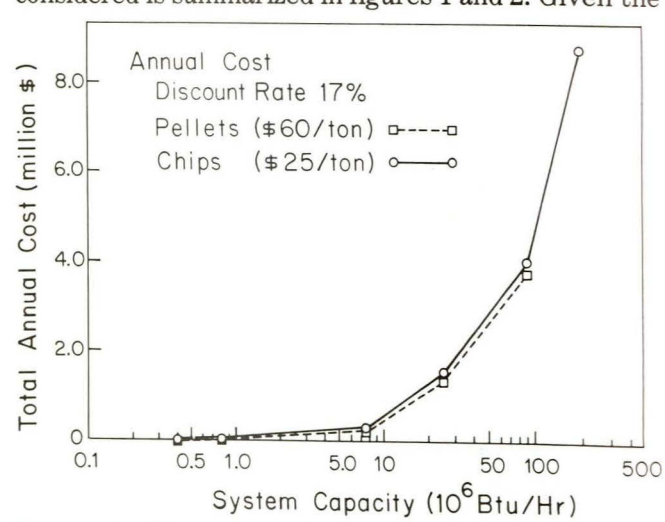

Figure 2.—*Total annual cost of densified wood and chip fuel energy systems for six representative energy users. Costs are presented for the largest storage capacity option of each system.*

assumptions and analysis procedure we used, a chip price of $25 per ton, and a pellet price of $60 per ton, the following conclusions can be drawn:

1. At the chip and pellet prices assumed in this analysis, densified wood fuel systems have a lower delivered energy cost and annual cost than chip systems of equivalent size and storage capacity. The lower costs result from the chip and pellet price differential and the improved handling and combustion properties of densified wood fuel.

2. Larger wood energy systems have lower delivered energy costs than small systems because the larger process heating systems operate more hours per year and take advantage of economies of scale.

3. The larger storage capacity required by chip systems results in larger delivered energy cost than for densified wood fuel systems of equivalent size. Again, this is a result of the improved storage and handling properties of densified wood fuels.

4. Delivered energy costs for the specific systems studied did not always conform to anticipated trends, e.g., the increase in delivered energy cost between the 0.4 and 0.8 million Btu per hour systems. This was a result of the size and variety of storage, handling, and combustion equipment selected. A range of delivered energy costs where each system's specific variations have been smoothed is presented in figure 3. These results are more indicative of overall cost trends that occur with wood energy systems.

The following section shows how changes in several of the assumptions affect the delivered energy cost and annual cost of various-size wood energy systems. The variables and level of variation chosen for each assumption were:

Variable	Level
Wood fuel price	Chips—$15, $25, and $35 per ton Pellets—$50, $60, and $70 per ton
Interest rate	14, 17, and 20 percent
Non-fuel annual cost	± 25 percent

These values were selected arbitrarily and are not necessarily intended to predict future events. We calculated the delivered energy cost and annual cost of each system for each alternate condition using the assumptions and cost analysis procedure outlined in Steklenski and Haygreen 1983.

Conclusions regarding the sensitivity of the delivered energy cost to variations in fuel price, interest rate, and non-fuel annual cost are as follows:

1. Wood fuel price changes result in unit energy cost changes, which are equivalent for all systems. However, the annual cost of larger wood energy systems is more sensitive to fuel price than that of smaller systems because a larger proportion of total costs of large systems go for fuel. In addition, densified wood fuel systems are more sensitive to fuel price than chip systems.

2. The delivered energy cost, as well as the annual cost, of smaller wood energy systems is more sensitive to interest rates and non-fuel annual cost than that of larger systems because the proportion of capital and other costs except fuel is greater for small systems. In addition, chip systems are more sensitive than densified wood fuel systems.

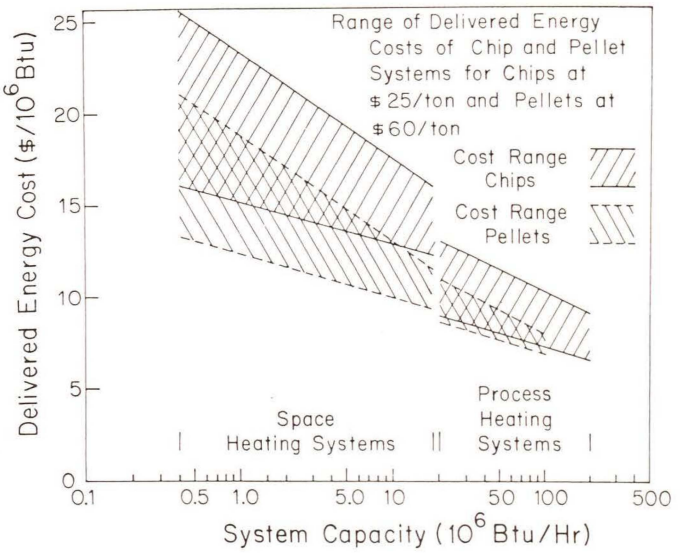

Figure 3.—*Range of delivered energy costs of densified wood and chip fuel space and process heating systems with a fuel price differential of $35 per ton.*

We also compared chip and densified wood fuel systems, using two fuel price scenarios. Systems using the lowest priced chips were compared with systems using the highest priced pellets (a $55 per ton differential); and systems using the highest priced chips were compared with systems using the lowest priced pellets (a $15 per ton differential).

The chip and pellet price differential is a major factor in determining the cost competitiveness between chip and densified wood fuel energy systems. In process energy systems, a fuel price differential of $40 to $50 per ton between chips and pellets will result in equivalent delivered energy costs. This differential in space heating systems, by contrast, ranges from $70 to $100 per ton. This indicates that densified wood fuel systems, such as those burning pellets, are more economical for systems with small energy requirements (less than 7.5 million Btu per hour); chip-fired systems are more economical for systems with larger energy requirements. Figure 4 presents this relationship graphically by assuming a $45 per ton price differential for the entire range of systems considered.

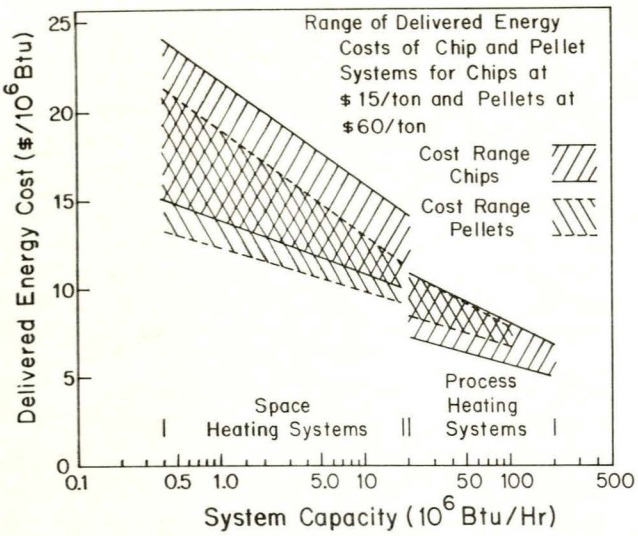

Figure 4.—*Range of delivered energy costs of densified wood and chip fuel space and process heating systems with a fuel price differential of $45 per ton.*

CONCLUSION

Facilities and individuals base their choice of an energy system primarily on annual cost savings. A decision to convert to wood fuel is evaluated on the basis of anticipated annual fuel cost savings versus the incremental increase in capital investment cost, operating and maintenance costs, and other miscellaneous costs. An understanding of this relationship and the results of the economic sensitivity analysis presented above can be useful in developing public policy and legislation to enhance the conversion of additional facilities to wood fuel energy systems.

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Achieving wood energy potentials: evidence in northeastern Minnesota. 1987. Gen. Tech. Rep. NC-114. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 82 p.

A study of wood energy potential in northeastern Minnesota concludes that (1) the forests of the region could support a much larger wood energy harvest without significant cost increases for other forest products; (2) existing stands are predominantly overmature and cutting more now will enhance future wood supplies for all users; (3) converting to wood energy could reduce fuel costs for many consumers, businesses, and industries; (4) a wood energy industry would increase the region's output and employment and reduce the costs of its exports; and (5) most barriers to expanded wood energy use are institutional, not technical. Policies to encourage wood energy development can be developed at low cost.

KEY WORDS: Timber supply, economic impact, forest policy, harvest scheduling, biomass energy.